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COMPUTER PROGRAMS FOR PREDICTING SUPERSONIC AND HYPERSONIC INTERFERENCE FLOW FIELDS AND HEATING

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16. Abstract

This report describes computer codes which calculate two-dimensional shock interference patterns. These codes compute the six types of interference flows as defined by Edney (Aeronaut. Res. Inst. of Sweden FFA Rep. 115). Results include properties of the inviscid flow field and the inviscid-viscous interaction at the surface along with peak pressure and peak heating at the impingement point.

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COMPUTER PROGRAMS FOR PREDICTING SUPERSONIC AND HYPERSONIC INTERFERENCE FLOW FIELDS AND HEATING

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SUMMARY

This paper describes computer programs which calculate peak pressure and heating for six types of two-dimensional interference flow patterns. These programs were used to obtain the theoretical values used in NASA TN D-7139. Depending upon the type of inviscid flow pattern, the pressure and heat-transfer peaks occurring at the impingement point are a result of shock—boundary-layer interaction, free shear-layer attachment, or supersonic jet impingement. Peak-heating correlations for laminar and turbulent shock—boundary-layer interactions are included in the programs for types I, II, V, and VI interference patterns. Heating correlations for laminar and turbulent reattaching shear layers obtained from separation studies are included in the program for type III interference.

INTRODUCTION

Shock interference heating is a problem in the design of the thermal protection system and structural components of supersonic and hypersonic vehicles (refs. 1 and 2) such as the space shuttle, hypersonic research aircraft, and hypersonic cruise vehicle. Small areas of high heat transfer and pressure can occur on the vehicle surface because of the influence of an impinging shock upon the local flow. Edney (ref. 1) made a detailed study of interference flows and defined six types of shock interference patterns. He found that the peaks of surface pressure and heat transfer are caused by shock—boundary-layer interactions, free shear-layer attachments, or supersonic jet impingement, depending on the type of pattern.

Edney also developed flow models and methods of calculating the flow field for each type. Methods were developed to compute the peak pressure for the shear-layer attackment and the peak pressure and heat transfer for the supersonic jet impingement. Semi-empirical methods for calculating peak pressures and heat transfer for all six types of interference patterns were developed in reference 2 by using the flow models of reference 1 and the heat-transfer correlations of Bushnell and Weinstein (shear-layer attachment, ref. 3) and Markarian (shock-boundary interaction, ref. 4). Methods similar to those of reference 1 are also discussed in reference 5.

This report describes computer programs generated during the investigation reported in reference 2 for six types of interference patterns. The flow model for each type was developed on the basis of two-dimensional flow. Perfect-gas relations from reference 6 were used to obtain the flow conditions in the inviscid flow field. Sutherland's viscosity formula for air (from ref. 6) is included in the programs; however, any perfect gas can be used by inserting an alternate viscosity law. Peak pressure and heat transfer are nondimensionalized with respect to reference values (at the stagnation point on a hemisphere or values ahead of the impingement point on a wedge). Each program requires certain input based on shock and model geometries.

These programs are written in FORTRAN IV language for the Control Data Corporation 6000 series computer under the SCOPE 3.0 operating system. The standard FORTRAN NAMELIST is used with $DATAIN as the NAMELIST name. Each program is presented in a separate part of the report (parts I to VI), and the subprograms common to more than one program are presented in part VII. A discussion concerning the application of the programs for a typical configuration is given in part VIII.

SYMBOLS

A	constant in equation (2)
a	speed of sound
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
$\left(\frac{du_w}{ds}\right)_{stag}$	stagnation velocity gradient on a sphere (eq. (6))
L_{SH}	shock displacement length (see figs. 5 and 6)
l_{SL}	shear-layer length (see eqs. (3) and (4) and fig. 5)
M	Mach number
N	exponent in equations (1) and (2)
N_{Pr}	Prandtl number

p	pressure
Q	heat-transfer rate
R_b	radius of sphere
R_{bj}	radius of "jet body" (see fig. 8)
R_c	radius of curvature of jet bow shock (see fig. 8)
s	surface coordinate (see fig. 8)
T	temperature
u	velocity
$\overline{w}$	jet width at jet bow shock (see figs. 7 and 8)
X_i	impingement locations on wedge (see fig. 3)
x	jet coordinate in horizontal plane (see fig. 7)
y	jet coordinate in vertical plane (see fig. 7)
α_j	jet impingement angle relative to local body slope (figs. 6 and 8)
β	shock angle
β_b	bow shock angle
β_i	impinging shock angle
γ	ratio of specific heats
δ_{js}	standoff distance of jet bow shock at stagnation streamline (see fig. 8)
δ_{SL}	shear-layer thickness at wall (eqs. (2) to (4))
θ	flow deflection angle

θ_b	local body slope
θ_i	shock generator angle
$\bar{\theta}_5$	shear-layer angle relative to local body slope (see fig. 5 and eq. (2))
μ	viscosity
ρ	density

Subscripts:

1 to 8	regions
aw	adiabatic wall
j	jet
pk	peak
ref	reference
stag	stagnation-point value on sphere
u	undisturbed value
w	wall
wedge	wedge value (undisturbed)
∞	free stream

SPECIAL NOTATION

BS	bow shock (fig. 1)
IP	impingement point (fig. 1)
IS	impinging shock (fig. 1)

SL shear layer (fig. 1)

TS transmitted shock (fig. 1)

wrt with respect to

1, 2, 3, . . ., 8 regions in shock pattern (figs. 3 to 5, 7, 9, and 10)

TYPES OF INTERFERENCE

The six types of interference flow patterns from reference 1 are shown in figure 1. The peak heating at the impingement point IP for types I, II, and V is the result of a shock—boundary-layer interaction. Type III interference is characterized by an attaching shear layer. The impinging supersonic jet of type IV interference causes the most intense heating. An expansion-fan—boundary-layer interaction occurs in type VI and results in a reduction in pressure and heat transfer. Figure 2 shows how the types of interference patterns change on a hemisphere as the impinging shock moves around the body.

PART I – TYPE I INTERFERENCE

PROBLEM DISCUSSION

A type I interference pattern occurs when two weak shocks of opposite families (BS and IS) intersect, as illustrated in figure 1(a). The actual heating rise is the result of the transmitted impinging shock TS interacting with the boundary layer. This type of interference pattern will occur when the flow upstream of the impingement point is supersonic, or in the case of a blunt body, it will take place well below the sonic point. (See fig. 2.)

Since the flow field associated with type I interference is supersonic throughout, it is described in some detail. The following discussion concerns both the calculation of the inviscid flow field and the prediction of the associated peak pressure and heat transfer.

The flow model used in the present analysis consisted of weak bow and impinging shocks generated by two wedges. A shear layer bounded by the transmitted bow and impinging shocks occurs at the shock intersection A, as shown in figure 3. Across the shear layer it is necessary that the static pressures be equal $(p_4 = p_5)$ and the flow velocities be parallel. An iterative procedure is utilized to obtain the strength of the transmitted shocks and the orientation of the shear layer relative to the free-stream direction which satisfy these conditions.

The flow conditions in regions 2 and 3 are calculated from the Rankine-Hugoniot equations of reference 6 once the flow conditions in region 1 and the strengths of the bow shock and impinging shocks are specified. These flow conditions (region 1) consist of Mach number, stagnation or static pressure and temperature, ratio of specific heats, and various other constants associated with the free-stream gas. To start the iterative procedure, a value of the flow deflection is assumed and conditions in regions 4 and 5 are computed, again by using the Rankine-Hugoniot equations. If the pressures are equal, within a specified tolerance, the calculation is terminated; if not equal, the shear-layer deflection angle is increased incrementally toward the region with the lower pressure, and the procedure is repeated. From the strength of the transmitted impinging shock and the orientation of the body surface at the impingement point, it is possible to calculate conditions in region 6 by use of the Rankine-Hugoniot equations. Two cases must be considered: regular reflection and Mach reflection (ref. 7). The former occurs for local Mach numbers sufficiently high and shock angles sufficiently low to insure an attached shock system at the wall. The latter case occurs if this condition is not satisfied, and the pressure rise at the wall is approximated by using normal-shock relations.

The increase in heating resulting from the shock—boundary-layer interaction at IP is determined from the empirical correlations of Markarian (ref. 4), which are based upon the inviscid pressure rise across the interaction region. These correlations are of the form

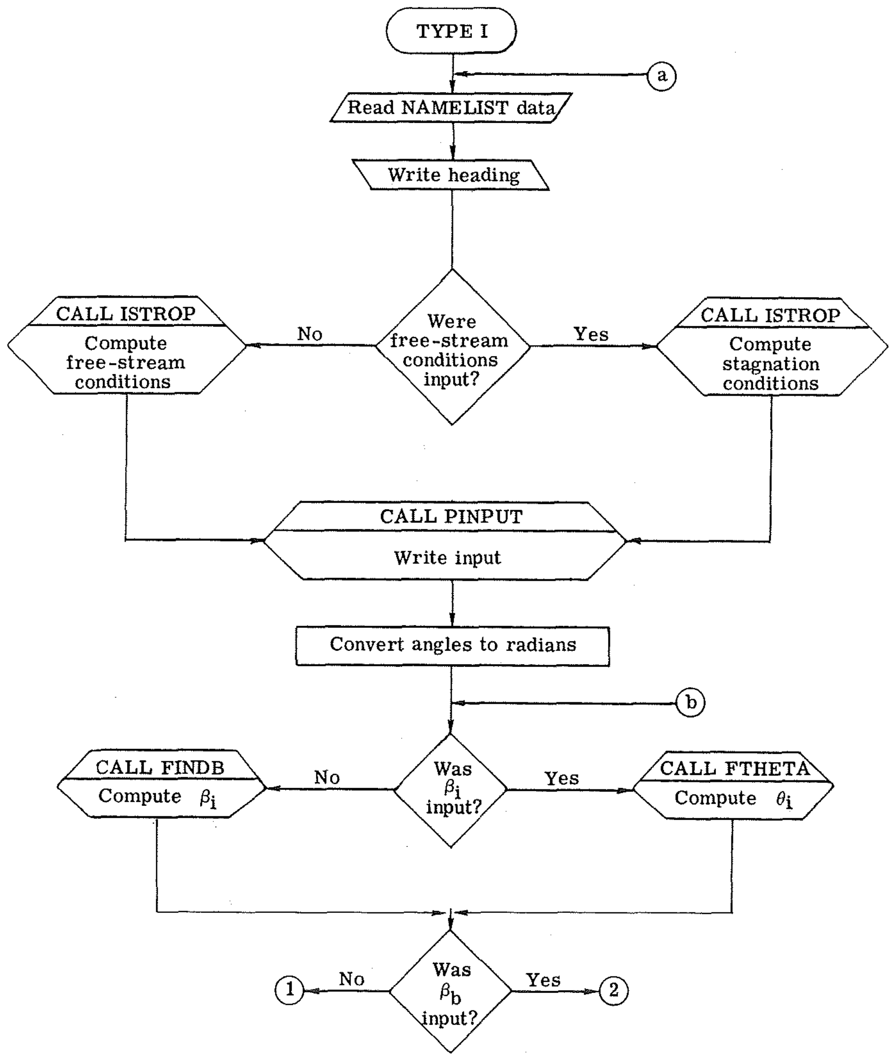
$$\frac{Q_{pk}}{Q_u} = \left(\frac{p_{pk}}{p_u}\right)^N \tag{1}$$

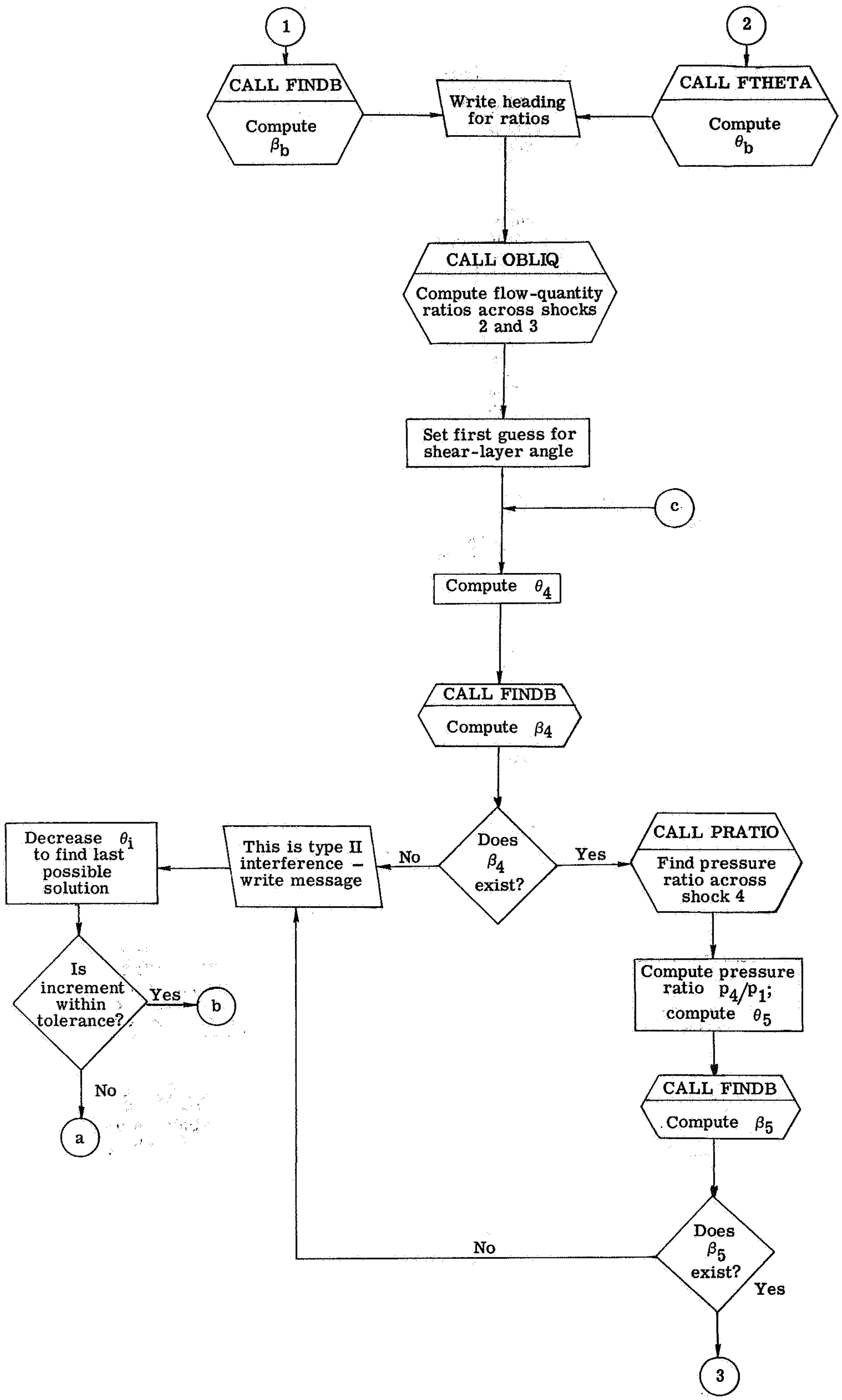
where N is a constant which is dependent upon whether the interaction is laminar or turbulent and the ratio p_{pk}/p_u is p_6/p_2. For laminar and turbulent interactions, N is 1.29 and 0.85, respectively. Calculation of the peak heating requires a knowledge of the undisturbed, or reference, heat transfer Q_u ahead of the interaction. The location of the impingement point X_i and the state of the boundary layer (laminar or turbulent) on the wedge (present flow model) must be specified in order to determine Q_u. Values of Q_u are obtained by using the reference temperature method of Eckert (ref. 8) for laminar and turbulent boundary layers.

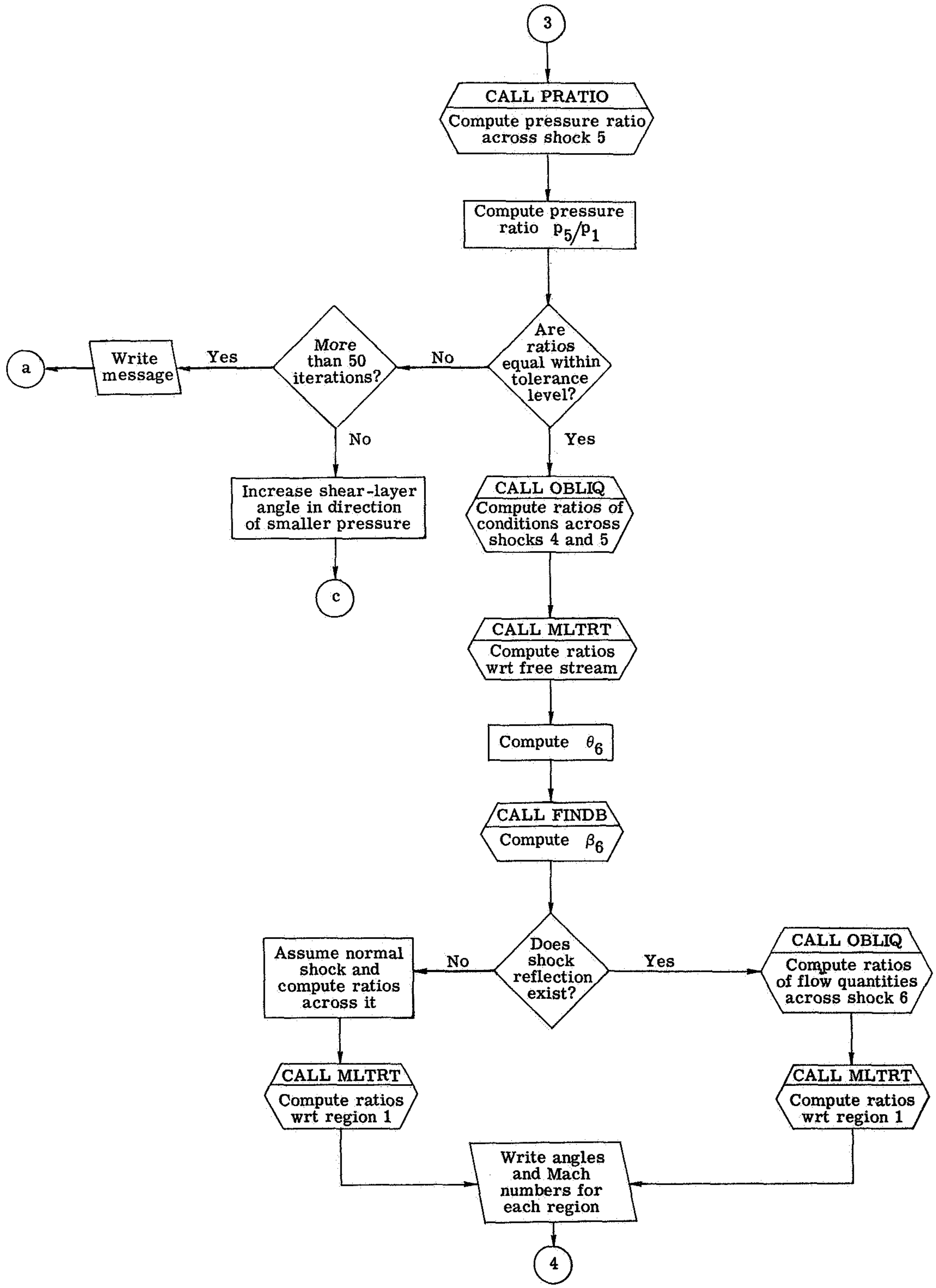
PROGRAM DESCRIPTION

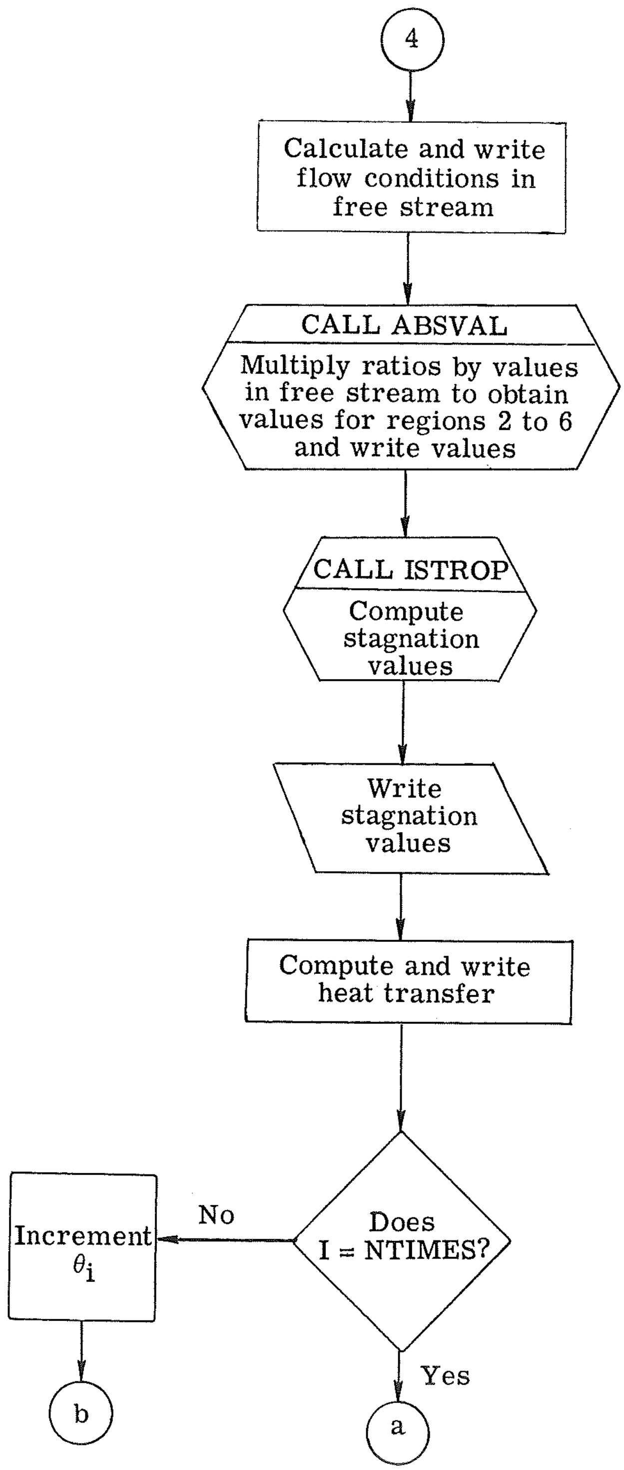
The main program reads the input, calls the various subprograms, controls the iterative solution to determine the deflection angle of the shear layer at point A (fig. 3), and computes the heat transfer. Subprogram FTHETA is called to compute the flow deflection angles, and FINDB is called to compute the shock angles in each region. The subprograms OBLIQ, MLTRT, ABSVAL, PRATIO, and ISTROP compute flow variables and ratios of the flow variables. PINPUT prints input variables. The flow charts and listings of these subprograms are presented in part VII. The flow diagram and listing for the main program follow.

Program Flow Chart – Main




1
2
CALL FINDB
Compute β_b
Write heading for ratios
CALL FTHETA
Compute θ_b
CALL OBLIQ
Compute flow-quantity ratios across shocks 2 and 3
Set first guess for shear-layer angle
c
Compute θ_4
CALL FINDB
Compute β_4
Does β_4 exist?
Yes
No
This is type II interference – write message
Decrease θ_i to find last possible solution
Is increment within tolerance?
Yes
b
No
a
CALL PRATIO
Find pressure ratio across shock 4
Compute pressure ratio p_4/p_1; compute θ_5
CALL FINDB
Compute β_5
Does β_5 exist?
No
Yes
3


3
CALL PRATIO
Compute pressure ratio across shock 5
Compute pressure ratio p_5/p_1
Are ratios equal within tolerance level?
No
More than 50 iterations?
Yes
Write message
a
No
Increase shear-layer angle in direction of smaller pressure
c
Yes
CALL OBLIQ
Compute ratios of conditions across shocks 4 and 5
CALL MLTRT
Compute ratios wrt free stream
Compute θ_6
CALL FINDB
Compute β_6
Does shock reflection exist?
No
Assume normal shock and compute ratios across it
CALL MLTRT
Compute ratios wrt region 1
Yes
CALL OBLIQ
Compute ratios of flow quantities across shock 6
CALL MLTRT
Compute ratios wrt region 1
Write angles and Mach numbers for each region
4


4
Calculate and write flow conditions in free stream
CALL ABSVAL
Multiply ratios by values in free stream to obtain values for regions 2 to 6 and write values
CALL ISTROP
Compute stagnation values
Write stagnation values
Compute and write heat transfer
Does I = NTIMES?
No
Increment θ_i
Yes
b
a

Program Listing – Main

```
      PROGRAM SHOCK(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C     ..................................................................
C
C     THIS PROGRAM PERFORMS A TYPE I SHOCK INTERFERENCE PATTERN
C     FOR  TWO DIMENSIONAL FLOW
C
C     ..................................................................
      DIMENSION T2STAR(2), RHO2STR(2), V2STAR(2), REY2STR(2), HR(2), QFP
     1(2), HPK(2), QPK(2), STN2(2)
      DIMENSION STN1(2)
      DIMENSION PN(2)
      DIMENSION AA(2), RN(2)
      DIMENSION RP(2), TR(2), HFP(2)
      COMMON  PZ, RHOZ, TZ, P1OPZ, RHO1OZ, T1OTZ,
     1        PZ2, RHOZ2, TZ2, P2OPZ2, RHO2Z2, T2OTZ2,
     2        PZ3, RHOZ3, TZ3, P3OPZ3, RHO3Z3, T3OTZ3,
     3        PZ4, RHOZ4, TZ4, P4OPZ4, RHO4Z4, T4OTZ4,
     4        PZ5, RHOZ5, TZ5, P5OPZ5, RHO5Z5, T5OTZ5,
     5        PZ6, RHOZ6, TZ6, P6OPZ6, RHO6Z6, T6OTZ6,
     6        P2OP1, RHO2O1, T2OT1, A2OA1, U2OU1,
     7        P3OP2, RHO3O2, T3OT2, A3OA2, U3OU2,
     8        P3OP1, RHO3O1, T3OT1, A3OA1, U3OU1,
     9        P4OP2, RHO4O2, T4OT2, A4OA2, U4OU2,
     $        P4OP1, RHO4O1, T4OT1, A4OA1, U4OU1,
     $        P5OP3, RHO5O3, T5OT3, A5OA3, U5OU3,
     $        P6OP2, RHO6O2, T6OT2, A6OA2, U6OU2,
     $        P6OP4, RHO6O4, T6OT4, A6OA4, U6OU4,
     $        P5OP1, RHO5O1, T5OT1, A5OA1, U5OU1,
     $        P6OP1, RHO6O1, T6OT1, A6OA1, U6OU1
      COMMON  P1, RHO1, T1, A1, U1, VISC1, REY1,
     1        P2, RHO2, T2, A2, U2, VISC2, REY2,
     2        P3, RHO3, T3, A3, U3, VISC3, REY3,
     3        P4, RHO4, T4, A4, U4, VISC4, REY4,
     4        P5, RHO5, T5, A5, U5, VISC5, REY5,
     5        P6, RHO6, T6, A6, U6, VISC6, REY6
      NAMELIST /DATAIN/ RM1,GAMMA,THETAB,THETAI,TINCR,NTIMES,IPT,T,P,AMW
     1,TREF,VREF,XL,S,TWALL,CP,PR,RUN,ANGLE,ANGLE2,TOL
C     TOL IS THE CONVERGENCE CRITERION FOR CONDITION 1 AND 2
C     INITIALIZE CONSTANTS
      BETA=4HBETA
      IO=1
      PN(1)=1.29
      PN(2)=0.85
      AA(1)=0.332
      AA(2)=.185
      RN(1)=-.5
      RN(2)=-2.584
C     ..................................................................
C
C     INPUT DATA
C
C     ..................................................................
101   READ (5,DATAIN)
      IF (ENDFILE 5) 102,103
102   STOP
103   CONTINUE
```

```
      WRITE(6,DATAIN)
      RR(1)=SQRT(PR)
      RR(2)=PR**(1./3.)
      THBDEG=THETAB
      THIDEG=THETAI
      WRITE (6,144) RUN
C     GAS CONSTANT (FT-LBF/LBM-R)
      R=1544.3/AMW
C     DENSITY (SLUG/CU-FT)
      RHO=P*144./(32.2*R*T)
      IF (IPT) 104,104,105
C     STAGNATION CONDITIONS
104   TZ=T
      RHOZ=RHO
      PZ=P
      GO TO 106
C     FREE STREAM CONDITIONS
105   T1=T
      P1=P
      RHO1=RHO
106   CONTINUE
      CALL ISTROP (GAMMA,RM1,P1,PZ,P1OPZ,IPT)
C     PRINT OUT INPUT VARIABLES
      CALL PINPUT (RM1,GAMMA,IPT,T,P,AMW,TREF,VREF,XL,S,TWALL,CP,PR)
      WRITE (6,145) XL
      ITYP2=0
C               ITYP2 = 0    NORMAL
C     CONVERT ANGLES TO RADIANS
      TINCR=TINCR/57.296
      THETAB=THBDEG/57.296
      THETAI=THETAI/57.296
      INPRB=0
      INPBI=0
C     SAVE THETA AND TINCR TO RESTORE AFTER CONDITION 2
      SINCR=TINCR
      STHETA=THETAI
C     INITIALIZE THEOLD AND THIOLD FOR INITIAL ESTIMATE FOR THETAF
      THEOLD=THETAI+THETAB
      THIOLD=THETAI
C     THIEST SAVES ORIGINAL THETAI IN CASE MULTIPLE THETAB'S ARE READ
      THIEST=THIDEG
      DO 142 I=1,NTIMES
107   WRITE (6,148)
      IF (ANGLE.NE.BETA) GO TO 108
C     BETAI WAS INPUT INSTEAD OF THETAI
      BETAI=THETAI
      INPBI=1
      THETAI=FTHETA(GAMMA,RM1,BETAI)
      GO TO 109
108   BETAI=FINDB(GAMMA,RM1,THETAI,IERROR)
      IF (IERROR-2) 109,109,111
109   IF (ANGLE2.NE.BETA) GO TO 110
C     BETAB WAS INPUT INSTEAD OF THETAB
      BETAB=THETAB
      INPRB=1
      THETAB=-FTHETA(GAMMA,RM1,ABS(BETAB))
      GO TO 112
110   BETAB=-FINDB(GAMMA,RM1,-THETAB,IERROR)
      IF (IERROR-2) 112,112,111
111   GO TO 143
```

```
112   THBDEG=THETAB*57.296
      THIDEG=THETAI*57.296
      WRITE (6,146) THIDEG,THBDEG
      WRITE (6,147)
C     ..............................................................
C               ERRORS IN FINDING BETA
C               IERROR = 1  ONE SOLUTION WAS FOUND, CONTINUE
C                        2  SOLUTION DID NOT CONVERGE, USE LAST B COMPUTE
C                        3  NO SOLUTION WAS FOUND, START NEW CASE
C                        4  NOT DEFINED
C     ..............................................................
      SINBI=SIN(BETAI)
      SINBB=SIN(BETAB)
      BBDEG=BETAB*57.296
      BIDEG=BETAI*57.296
C     FIND RATIOS FOR REGION 2 WITH RESPECT TO REGION 1
      CALL OBLIQ (GAMMA,RM1,THETAB,BETAB,RM2,P2OP1,1,2,IO)
C     FIND RATIOS FOR REGION 3 WITH RESPECT TO REGION 1
      CALL OBLIQ (GAMMA,RM1,THETAI,BETAI,RM3,P3OP1,1,3,IO)
      ISW=0
C     ..............................................................
C
C     CONDITION 1
C     ITERATE ON THETAF UNTIL P4 = P5
C
C     ..............................................................
      IT=1
      DTHETA=.01
      THETAF=THFOLD+THETAI-THIOLD
113   THETA4=-THETAB+THETAF
      BETA4=FINDB(GAMMA,RM2,THETA4,IERROR)
      IF (IERROR-3) 114,127,111
114   P4OP2=PRATIO(GAMMA,RM2,SIN(BETA4))
      P4OP1=P4OP2*P2OP1
      THETA5=-(THETAI-THETAF)
      BETA5=-FINDB(GAMMA,RM3,ABS(THETA5),IERROR)
      IF (IERROR-3) 115,127,111
115   P5OP3=PRATIO(GAMMA,RM3,SIN(BETA5))
      P5OP1=P5OP3*P3OP1
      IT=IT+1
      IF (ABS(P5OP1-P4OP1)-.001) 128,128,116
116   IF (IT-50) 118,118,117
117   WRITE (6,149) P5OP1,P4OP1
      GO TO 143
C     INCREASE THETAF IN THE DIRECTION OF THE SMALLER PRESSURE
118   IF (P5OP1-P4OP1) 119,128,123
C               HAVE SIGNS SWITCHED
119   IF (ISW) 122,120,121
120   ISW=-1
      GO TO 122
121   THETAF=THETAF-DTHETA
      DTHETA=DTHETA/10.0
      GO TO 113
122   THETAF=THETAF-DTHETA
      GO TO 113
123   IF (ISW) 125,124,126
124   ISW=1
      GO TO 126
125   THETAF=THETAF+DTHETA
      DTHETA=DTHETA/10.0
      GO TO 113
```

```
126   THETAF=THETAF+DTHETA
      GO TO 113
127   TFDEG=THETAF*57.296
      WRITE (6,150)
      ITYP2=4
      TINCR=TINCR/2.
      THETAI=THETAI-TINCR
      IF (TINCR-TOL) 143,107,107
C     ..................................................................
C
C     ITERATION ON P4 AND P5 IS COMPLETED. USE COMPUTED THETAF TO CALCUL
C     CONDITIONS 4-6.
C
C     ..................................................................
128   SINB4=SIN(BETA4)
      SINB5=SIN(BETA5)
C     FIND RATIOS FOR REGION 4 WITH RESPECT TO REGION 2
      CALL CBLIQ (GAMMA,RM2,THETA4,BETA4,RM4,P4OP2,2,4,IO)
C     FIND RATIOS FOR REGION 5 WITH RESPECT TO REGION 3
      CALL CBLIQ (GAMMA,RM3,ABS(THETA5),ABS(BETA5),RM5,P5OP3,3,5,IO)
      TFDEG=THETAF*180./3.1416
      THFOLD=THETAF
      THIOLD=THETAI
C     FIND RATIOS FOR REGION 4 WITH RESPECT TO REGION 1
      CALL MLTRT (P4OP2,P2OP1,P4OP1,1,4,IO)
C     FIND RATIOS FOR REGION 5 WITH RESPECT TO REGION 1
      CALL MLTRT (P5OP3,P3OP1,P5OP1,1,5,IO)
      THETA6=THETAB-THETAF
      IERROR=1
      BETA6=-FINDB(GAMMA,RM4,ABS(THETA6),IERROR)
      IF (IERROR-3) 133,129,133
C
C     CONDITION 2
C     SHOCK REFLECTION NOT POSSIBLE. ITERATE ON THETAI TO FIND LAST
C     POSSIBLE SHOCK REFLECTION.
C
129   RM2SQ=RM2*RM2
      BETA6=1.5708
      WRITE (6,151)
C     IF ITYP2.GT.3 THEN ITERATION ON CONDITION 2 IS COMPLETED.
      IF (ITYP2-3) 130,132,132
130   ITYP2=1
      THETAI=THETAI-TINCR
      IF (TINCR-TOL) 131,132,132
C     ITERATION HAS CONVERGED. RETURN TO INCREMENTING THETA NORMALLY
131   TINCR=SINCR
      THETAI=STHETA+TINCR
      ITYP2=3
C     BECAUSE OBLIQUE SHOCK REFLECTION NOT POSSIBLE BETWEEN 4 AND 6 USE
C     NORMAL SHOCK RELATIONS BETWEEN 6 AND 2
132   P6OP2=1.+2.*GAMMA/(GAMMA+1.)*(RM2SQ-1.)
      RHO6O2=(GAMMA+1.)*RM2SQ/((GAMMA-1.)*RM2SQ+2.)
      T6OT2=(2.*GAMMA*RM2SQ-(GAMMA-1.))*((GAMMA-1.)*RM2SQ+2.)
      T6OT2=T6OT2/((GAMMA+1.)**2*RM2SQ)
      A6OA2=ARATIO(T6OT2)
      RM6=SQRT(((GAMMA-1.)*RM2SQ+2.)/(2.*GAMMA*RM2SQ-(GAMMA-1.)))
      U6OU2=A6OA2*RM6/RM2
      WRITE (6,152) P6OP2,RHO6O2,T6OT2,A6OA2,U6OU2
C     FIND RATIOS FOR REGION 6 WITH RESPECT TO REGION 1
      CALL MLTRT (P6OP2,P2OP1,P6OP1,1,6,IO)
      GO TO 134
```

```
C     SHOCK REFLECTION POSSIBLE. USE OBLIQUE SHOCK RELATION BETWEEN 6 AN
133   CALL OBLIQ (GAMMA,RM4,ABS(THETA6),ABS(BETA6),RM6,P6OP4,4,6,IO)
      P6OP2=P6OP4*P4OP2
C     FIND RATIOS FOR REGION 6 WITH RESPECT TO REGION 1
      CALL MLTRT (P6OP4,P4OP1,P6OP1,1,6,IO)
C     ..................................................................
C
C     WRITE THETA AND BETA FOR EACH REGION
C
C     ..................................................................
134   WRITE (6,153)
C     WRITE  THETA AND BETA FOR REGION 2
      THFDEG=THETAF*57.296
      THDEG=THBDEG
      BETDEG=BETAB*57.296
      ABSTH=THBDEG
      ABSBT=BETDEG
      J=2
      WRITE (6,154) J,THDEG.BETDEG,ABSTH,ABSBT,RM1,RM2
C     WRITE THETA AND BETA FOR REGION 3
      ABSTH=THIDEG
      ABSBT=BIDEG
      J=3
      WRITE (6,154) J,THIDEG,BIDEG,ABSTH,ABSBT,RM1,RM3
C     WRITE THETA AND BETA FOR REGION 4
      THDEG=THETA4*57.296
      BETDEG=BETA4*57.296
      ABSTH=THFDEG
      ABSBT=BETDEG+THBDEG
      J=4
      WRITE (6,154) J,THDEG,BETDEG,ABSTH,ABSBT,RM2,RM4
C     WRITE THETA AND BETA FOR REGION 5
      THDEG=THETA5*57.296
      BETDEG=BETA5*57.296
      ABSTH=THFDEG
      ABSBT=BETDEG+THIDEG
      J=5
      WRITE (6,154) J,THDEG,BETDEG,ABSTH,ABSBT,RM3,RM5
C     WRITE THETA AND BETA FOR REGION 6
      THDEG=THETA6*57.296
      BETDEG=BETA6*57.296
      ABSTH=THBDEG
      IF (BETA6.EQ.1.5708) GO TO 135
      ABSBT=BETDEG+THFDEG
      RM=RM4
      GO TO 136
135   ABSBT=BETDEG+THBDEG
      RM=RM2
136   J=6
      WRITE (6,154) J,THDEG,BETDEG,ABSTH,ABSBT,RM,RM6
C     ..................................................................
C
C     CALCULATE AND WRITE PARAMETER VALUES FOR EACH REGION
C
C     ..................................................................
      VISC1=VISCJ(VREF,TREF,T1,S)
      A1=SQRT(32.2*GAMMA*R*T1)
      U1=A1*RM1
      REY1=RHO1*U1/VISC1
      WRITE (6,155)
      WRITE (6,156)
C     WRITE ABSOLUTE VALUES FOR REGION 1
```

```
      J=1
      WRITE (6,157) J,P1,RHO1,T1,A1,U1,VISC1,REY1,RM1
C     WRITE ABSOLUTE VALUES FOR REGION 2
      J=2
      CALL ABSVAL (P2OP1,P1,P2,VREF,TREF,S,J,IO,RM2)
C     WRITE ABSOLUTE VALUES FOR REGION 3
      J=3
      CALL ABSVAL (P3OP1,P1,P3,VREF,TREF,S,J,IO,RM3)
C     WRITE ABSOLUTE VALUES FOR REGION 4
      J=4
      CALL ABSVAL (P4OP1,P1,P4,VREF,TREF,S,J,IO,RM4)
C     WRITE ABSOLUTE VALUES FOR REGION 5
      J=5
      CALL ABSVAL (P5OP1,P1,P5,VREF,TREF,S,J,IO,RM5)
C     WRITE ABSOLUTE VALUES FOR REGION 6
      J=6
      CALL ABSVAL (P6OP1,P1,P6,VREF,TREF,S,J,IO,RM6)
C     ..................................................................
C
C     CALCULATE AND WRITE STAGNATION VALUES FOR EACH REGION
C
C     ..................................................................
      WRITE (6,159)
      J=1
      WRITE (6,157) J,PZ,RHOZ,TZ
      J=2
      CALL ISTROP (GAMMA,RM2,P2,PZ2,P2OPZ2,2)
      PZ2OZ=PZ2/PZ
      WRITE (6,158) J,PZ2,RHOZ2,TZ2,PZ2OZ
      J=3
      CALL ISTROP (GAMMA,RM3,P3,PZ3,P3OPZ3,3)
      PZ3OZ=PZ3/PZ
      WRITE (6,158) J,PZ3,RHOZ3,TZ3,PZ3OZ
      J=4
      CALL ISTROP (GAMMA,RM4,P4,PZ4,P4OPZ4,4)
      PZ4OZ=PZ4/PZ
      WRITE (6,158) J,PZ4,RHOZ4,TZ4,PZ4OZ
      J=5
      CALL ISTROP (GAMMA,RM5,P5,PZ5,P5OPZ5,5)
      PZ5OZ=PZ5/PZ
      WRITE (6,158) J,PZ5,RHOZ5,TZ5,PZ5OZ
      J=6
      CALL ISTROP (GAMMA,RM6,P6,PZ6,P6OPZ6,6)
      PZ6OZ=PZ6/PZ
      WRITE (6,158) J,PZ6,RHOZ6,TZ6,PZ6OZ
C     ..................................................................
C
C     CALCULATE AND WRITE STANTON NUMBER, FLAT PLATE HEAT TRANSFER
C     COEFFICIENT(HFP), AND HEATING RATE(QFP)  IN REGION 2
C
C     ..................................................................
C     J = 1 IS LAMINAR AND J=2 IS TURBULENT
      DO 137 J=1,2
C     RECOVERY TEMPERATURE
      TR(J)=T2+RR(J)*(TZ-T2)
C     ECKERT≠S REFERENCE TEMPERATURE
      T2STAR(J)=.5*(TWALL+T2)+.22*(TR(J)-T2)
      RHO2STR(J)=144.*P2/(32.2*R*T2STAR(J))
      V2STAR(J)=VISCJ(VREF,TREF,T2STAR,S)
      REY2STR(J)=RHO2STR(J)*U2*XL/V2STAR(J)
```

```
C       LOCAL INCOMPRESSIBLE STANTON NUMBER IN REGION 2 AT IMPINGEMENT
        CF2=AA(J)*REY2STR**RN(J)
        IF (J.EQ.2) CF2=AA(J)*ALOG10(REY2STR)**RN(J)
        STN2(J)=CF2*PR**(-2./3.)
C       COMPRESSIBLE FLAT PLATE HEAT TRANSFER COEF(BTU/SEC-FT2-R)
        HFP(J)=STN2(J)*RHO2STR*U2*CP/778.
C       FREE STREAM STANTON NUMBER
        STN1(J)=778.*HFP(J)/(RHO1*U1*CP)
C       FLAT PLATE HEATING RATE(BTU/SEC-FT2)
        QFP(J)=HFP(J)*(TR(J)-TWALL)
C       MARKARIAN HEAT TRANSFER RATIOS
        HR(J)=P60P2**PN(J)
C       PEAK HEATING RATE
        QPK(J)=HR(J)*QFP(J)
C       PEAK HEAT TRANSFER COEF
137     HPK(J)=HFP(J)*HR(J)
        WRITE (6,160)
        WRITE (6,161) QFP(1),HFP(1),STN2(1),STN1(1),P60P2,HR(1),QPK(1),HPK
       1(1)
        WRITE (6,162) QFP(2),HFP(2),STN2(2),STN1(2),P60P2,HR(2),QPK(2),HPK
       1(2)
        WRITE (6,163)
C       ...............................................................
C
C       ITYP2 = 0 INCREMENT THETAI NORMALLY
C               1 AM ITERATING ON CONDITION 2,
C               3 THETAI IS BETWEEN CONDITION 1 AND 2. INCREMENT THETAI
C               4 AM ITERATING ON CONDITION 1
C
C       ...............................................................
138     ITYP=ITYP2+1
        GO TO (141,140,141,141,140,143), ITYP
C                 LAST ITERATION ON CONDITION 2. RETURN TO INCREMENTING
C                 NORMALLY
139     TINCR=SINCR
        THETAI=STHETA+TINCR
        ITYP2=ITYP2+2
        IF (ITYP2-3) 143,138,143
140     TINCR=TINCR/2.
        THETAI=THETAI+TINCR
        IF (TINCR-TCL) 139,107,107
141     STHETA=THETAI
142     THETAI=THETAI+TINCR
143     CONTINUE
C       RETURN THETAI AND TINCR TO ORIGINAL VALUES
        THETAI=THIFST
        TINCR=SINCR
        GO TO 101
C
144     FORMAT (1H1,9X,49HTHIS PROGRAM PERFORMS A TYPE I SHOCK INTERFERENC
       1E,8H PATTERN,//,13H RUN NUMBER   ,F5.2/)
145     FORMAT (16H XL(WALL LENGTH),15X,F15.6,4H  FT)
146     FORMAT (1H1,20HINPUT VARIABLES ARE /9H THETAI =,F9.4,19H DEG, AND
       1THETAB = ,F9.4,4H DEG//)
147     FORMAT (//12H RATIOS ARE /)
148     FORMAT (1H /)
149     FORMAT (1X,21H50 ITERATIONS, P5OP1=,F10.4,5X,7HP4OP1= ,F10.4)
150     FORMAT (//1X,37HTHIS IS A TYPE 2 INTERFERENCE PATTERN)
151     FORMAT (/1X,82HSHOCK REFLECTION NOT POSSIBLE AT THIS POINT - NORMA
       1L SHOCK BETWEEN 6 AND 2 ASSUMED/)
152     FORMAT (1X,6HP6/P2=,F8.4,5X,7HRHO6/2=,F8.4,5X,6HT6/T2=,F8.4,5X,6HA
       16/A2=,F8.4,5X,6HU6/U2=,F8.4)
```

```
153   FORMAT (//7H REGION,5X,14HRELATIVE ANGLE,10X,14HABSOLUTE ANGLE/9X,
     15HTHETA,8X,4HBETA,7X,5HTHETA,8X,4HBETA,29H  UPSTREAM MACH    LOCAL
     2 MACH)
154   FORMAT (1X,I1,4F12.4,2F15.4)
155   FORMAT (//7H REGION,10X,1HP,12X,3HRHO,11X,1HT,11X,1HA,11X,1HU,13X,
     12HMU,3X,11HREYNOLDS NO,9H  MACH NO)
156   FORMAT (14X,3HPSI,4X,10HSLUG/CU FT,5X,7HRANKINE,6X,6HFT/SEC,6X,6HF
     1T/SEC,4X,11HSLUG/FT-SEC,11X,4H1/FT)
157   FORMAT (1X,I5,F12.4,E15.5,3F12.4,2E15.5,F8.4)
158   FORMAT (1X,I5,F12.4,E15.5,3F12.6,2E15.5)
159   FORMAT (/1X,25HSTAGNATION CONDITIONS ARE/7H REGION,6X,5HPSTAG,12X,
     13HRHO,7X,5HTSTAG,4X,12HPSTAG/PSTAG1,/,14X,4HPSIA,4X,11HSLUGS/CU FT
     2,5X,7HRANKINE)
160   FORMAT (//14H HEAT TRANSFER,/17X,1HQ,14X,3HHFP,12X,8HSTANTON2,7X,8
     1HSTANTON1,7X,5HP6/P2,10X,2HHR,12X,3HQPK,12X,3HHPK)
161   FORMAT (8H LAMINAR,2X,8(E15.5))
162   FORMAT (10H TURBULENT,8(E15.5))
163   FORMAT (1H0,41HHFP = HEAT TRANSFER COEF(BTU/SQ FT-SEC-R)/35H Q    =
     1 HEAT TRANSFER(BTU/SQ FT-SEC))
      END
C     ..................................................................
C     ..................................................................
```

USAGE

Program SHOCK for a type I interference pattern uses the standard FORTRAN NAMELIST input with $DATAIN as the NAMELIST name. The input includes the flow conditions, gas properties, impinging flow deflection or shock angle, body angle, and impingement location on the body. The program can increase incrementally the shock generator angle and also predict when a type II interference pattern will occur.

A description of the input and output variables and a sample case are presented.

Input Description

The $DATAIN input for type I is as follows:

RUN — run number for identification

RM1 — M_∞, free-stream Mach number

GAMMA — c_p/c_v, ratio of specific heats

THETAI — θ_i, shock generator angle, deg; or β_i, impinging shock angle, deg

THETAB — θ_b, body angle, deg (input as negative angle); or β_b, bow shock angle, deg (input as negative angle)

TINCR	increment for θ_i, deg
NTIMES	number of times to increment θ_i
IPT	initial point; 0 for stagnation conditions, 1 for free-stream static conditions
T	temperature at IPT, ^oR
P	pressure at IPT, psia
AMW	molecular weight (used to compute gas constant)
TREF	reference temperature for computing viscosity, ^oR
VREF	reference viscosity for computing viscosity, slugs/ft-sec
S	Sutherland's constant in viscosity equation
XL	X_i, distance from leading edge to impingement point, ft
TWALL	temperature at wall, ^oR
CP	c_p, specific heat at constant pressure, ft-lbf/slug-^oR
PR	N_{Pr}, Prandtl number
ANGLE	THET if θ_i input; BETA if β_i input
ANGLE2	THET if θ_b input; BETA if β_b input
TOL	acceptable tolerance for equal pressures (0.001)

Output Description

The output consists of printing only. A heading and pertinent input for identification are printed before the calculated results.

RUN NUMBER	run number for identification
M1	M_∞, Mach number in free stream
GAMMA(CP/CV)	ratio of specific heats
TEMP AT POINT "IPT"	input as T, ^oR
PRES AT POINT "IPT"	input as P, psia
MOLECULAR WEIGHT	molecular weight (used to compute gas constant)
REFERENCE TEMP	reference temperature for computing viscosity, ^oR
REFERENCE VISCOSITY	reference viscosity for computing viscosity, slugs/ft-sec
S(SUTHERLAND NUMBER)	Sutherland's constant in viscosity equation
TEMP AT WALL	T_w, ^oR
CP	c_p, specific heat at constant pressure, ft-lbf/slug-^oR
PRANDTL NUMBER	N_{Pr}, Prandtl number
XL(WALL LENGTH)	X_i, length from leading edge to impingement point, ft
THETAI	θ_i, shock generator angle, deg
THETAB	θ_b, body angle, deg
P2/P1, etc.	p_2/p_1, etc., pressure ratios for regions listed
RHO2/1, etc.	ρ_2/ρ_1, etc., density ratios for regions listed
T2/T1, etc.	T_2/T_1, etc., temperature ratios for regions listed
A2/A1, etc.	a_2/a_1, etc., ratios of speeds of sound in regions listed
U2/U1, etc.	u_2/u_1, etc., velocity ratios for regions listed

RELATIVE ANGLE

THETA	flow angle relative to flow in upstream region, deg
BETA	shock angle relative to flow in upstream region, deg

ABSOLUTE ANGLE

THETA	flow angle relative to free-stream flow, deg
BETA	shock angle relative to free-stream flow, deg
UPSTREAM MACH	Mach number in upstream region
LOCAL MACH	local Mach number
REGION	region in shock pattern
P	static pressure in region, psia
RHO	static density in region, $slugs/ft^3$
T	static temperature in region, ^oR
A	speed of sound in region, ft/sec
U	velocity in region, ft/sec
MU	static viscosity in region, slugs/ft-sec
REYNOLDS NO	Reynolds number per foot in region
MACH NO	Mach number in region

The following stagnation conditions are then listed:

PSTAG	total pressure in region, psia
RHO	total density in region, $slugs/ft^3$

TSTAG	total temperature in region, $^{\circ}$R
PSTAG/PSTAG1	ratio of total pressure in region to free-stream total pressure

The pressure ratio and heat transfer for laminar and turbulent flow are listed as

Q	heat-transfer rate, Btu/ft^2-sec
HFP	flat-plate heat-transfer coefficient, Btu/ft^2-sec-$^{\circ}$R
STANTON2	local incompressible Stanton number
STANTON1	compressible free-stream Stanton number
P6/P2	peak pressure ratio
HR	Markarian heat-transfer ratio
QPK	peak heating rate
HPK	peak heat-transfer coefficient

Sample Case – Input

```
$DATAIN
RM1     =  0.6E+01,
GAMMA   =  0.14E+01,
THETAB  = -0.15E+02,
THETAI  =  0.5E+01,
TINCR   =  0.5E+01,
NTIMES  =  1,
IPT     =  0,
T       =  0.9E+03,
P       =  0.4E+03,
AMW     =  0.2897E+02,
TREF    =  0.53E+03,
```

```
VREF     =  0.3301E-06,
XL       =  0.25E+00,
S        =  0.1986E+03,
TWALL    =  0.55E+03,
CP       =  0.6006E+04,
PR       =  0.72E+00,
RUN      =  0.1E+01,
ANGLE    =  0.694047257651O9E+93,
ANGLE2   =  0.694047257651O9E+93,
TOL      =  0.1E-02,
$END
```

Sample Case – Output

```
        THIS PROGRAM PERFORMS A TYPE I SHOCK INTERFERENCE PATTERN

RUN NUMBER    1.00


INPUT VARIABLES ARE

M1                                      6.000
GAMMA(CP/CV)                            1.400000
TEMP AT POINT 0                       900.000000   RANKINE
PRES AT POINT 0                       400.000000   PSI
MOLECULAR WEIGHT                       28.970000
REFERENCE TEMP                        530.000000   RANKINE
REFERENCE VISCOSITY                  3.801000E-07  SLUG/(FT-SEC)
S(SUTHERLAND NUMBER)                  198.600
TEMP AT WALL                          550.000      RANKINE
CP                                   6006.000      FT-LBF/(SLUG-RANKINE)
PRANDTL NUMBER                          .720000
XL(WALL LENGTH)                         .250000    FT
```

INPUT VARIABLES ARE
THETAI = 5.0000 DEG, AND THETAB = -15.0000 DEG

RATIOS ARE

P2/P1=	6.0734	RHO2/1=	3.1011	T2/T1=	1.9585	A2/A1=	1.3995	U2/U1=	.9311
P3/P1=	2.0103	RHO3/1=	1.6306	T3/T1=	1.2328	A3/A1=	1.1103	U3/U1=	.9837
P4/P2=	1.6648	RHO4/2=	1.4337	T4/T2=	1.1612	A4/A2=	1.0776	U4/U2=	.9744
P5/P3=	5.0297	RHO5/3=	2.8268	T5/T3=	1.7793	A5/A3=	1.3339	U5/U3=	.9285
P4/P1=	10.1109	RHO4/1=	4.4459	T4/T1=	2.2742	A4/A1=	1.5081	U4/U1=	.9072
P5/P1=	10.1111	RHO5/1=	4.6093	T5/T1=	2.1936	A5/A1=	1.4811	U5/U1=	.9134
P6/P4=	1.5933	RHO6/4=	1.3907	T6/T4=	1.1457	A6/A4=	1.0704	U6/U4=	.9716
P6/P1=	16.1097	RHO6/1=	6.1828	T6/T1=	2.6056	A6/A1=	1.6142	U6/U1=	.8815

REGION	RELATIVE ANGLE THETA	BETA	ABSOLUTE ANGLE THETA	BETA	UPSTREAM MACH	LOCAL MACH
2	-15.0000	-22.6719	-15.0000	-22.6719	6.0000	3.9918
3	5.0000	13.1598	5.0000	13.1598	6.0000	5.3157
4	5.3083	18.2928	-9.6917	3.2928	3.9918	3.6095
5	-14.6917	-23.3922	-9.6917	-18.3922	5.3157	3.7001
6	-5.3083	-19.8941	-15.0000	-29.5858	3.6095	3.2765

REGION	P PSI	RHO SLUG/CU FT	T RANKINE	A FT/SEC	U FT/SEC	MU SLUG/FT-SEC	REYNOLDS NO 1/FT	MACH NO
1	.2533	1.93645E-04	109.7561	513.5679	3081.4074	8.46377E-08	7.05004E+06	6.0000
2	1.5387	6.00506E-04	214.9563	718.7182	2868.9832	1.72967E-07	9.96052E+06	3.9918
3	.5093	3.15760E-04	135.3111	570.2302	3031.1919	1.06990E-07	8.94597E+06	5.3157
4	2.5615	8.60919E-04	249.6093	774.4866	2795.4826	1.99702E-07	1.20513E+07	3.6095
5	2.5616	8.92574E-04	240.7624	760.6377	2814.4446	1.92989E-07	1.30168E+07	3.7001
6	4.0813	1.19726E-03	285.9789	828.9924	2716.2005	2.26522E-07	1.43563E+07	3.2765

STAGNATION CONDITIONS ARE

REGION	PSTAG PSIA	RHO SLUGS/CU FT	TSTAG RANKINE	PSTAG/PSTAG1
1	400.0000	3.72856E-02	900.0000	
2	231.0837	2.15402E-02	900.001065	.577709
3	386.5123	3.60280E-02	900.008771	.966281
4	228.0034	2.12530E-02	900.003197	.570008
5	258.7108	2.41152E-02	900.009631	.646777
6	225.6772	2.10362E-02	900.004664	.564193

HEAT TRANSFER

	Q	HFP	STANTON2	STANTON1	P6/P2	HR	QPK	HPK
LAMINAR	8.13165E-01	3.30239E-03	5.89526E-04	7.16914E-04	2.65250E+00	3.51978E+00	2.86216E+00	1.16237E-02
TURBULENT	4.02372E+00	1.44246E-02	2.57501E-03	3.13143E-03	2.65250E+00	2.29143E+00	9.22008E+00	3.30530E-02

HFP = HEAT TRANSFER COEF(BTU/SQ FT-SEC-R)
Q = HEAT TRANSFER(BTU/SQ FT-SEC)

PART II – TYPE II INTERFERENCE

PROBLEM DISCUSSION

A type II interference pattern occurs when two shocks of opposite families (BS and IS) intersect, as shown in figure 1(b). Both shocks are weak as in type I but are of such strength that in order to turn the flow, a Mach reflection must exist in the center of the flow field with an embedded subsonic region occurring between the intersection points (A and B) and the accompanying shear layers. (See p. 557 of ref. 7.) Type II interference occurs on a blunt body when the impinging shock intersects the bow shock near the sonic point, as shown in figure 2.

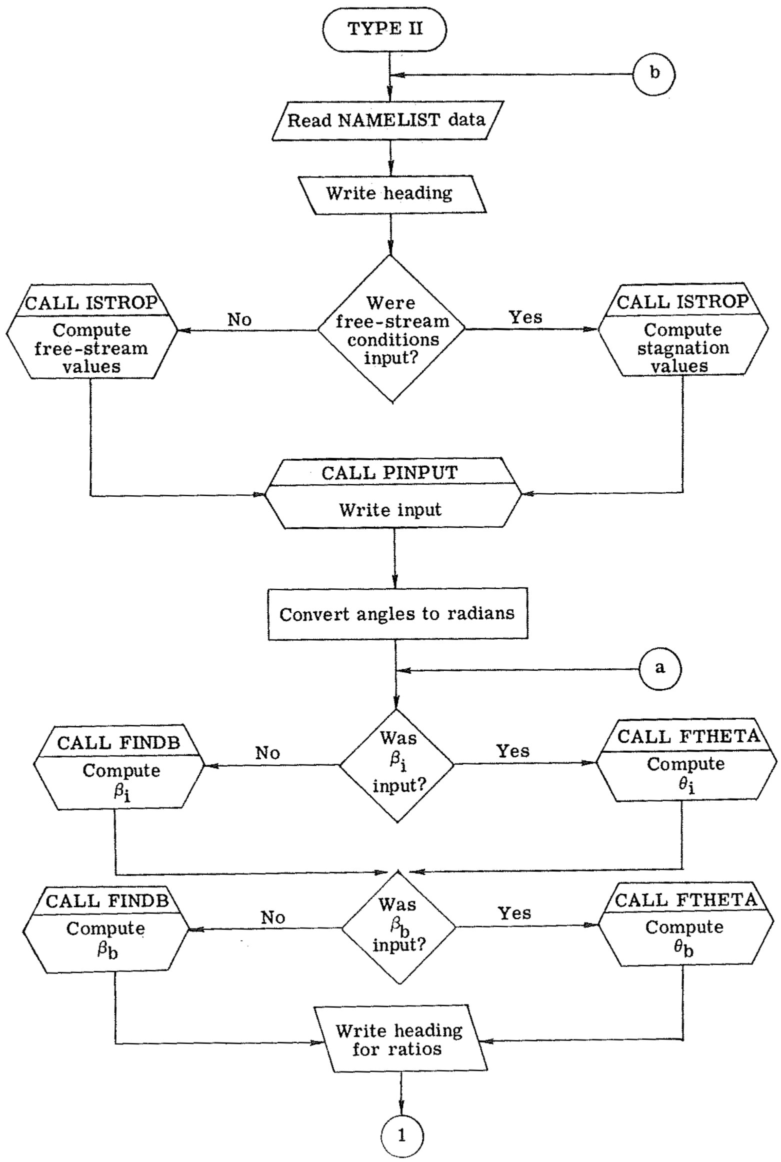
As for type I interference, the flow model consisted of a weak impinging shock and a stronger bow shock ($M_3 > M_2$) generated by two wedges, as illustrated in figure 4. A detailed analysis of the complete flow field is difficult because the extent of subsonic region 5 is unknown and depends on the size and shape of the body (ref. 1). The conditions in the supersonic regions (4 and 6) and the pressure ratio p_6/p_2 across the transmitted impinging shock at the shock—boundary-layer interaction IP can be calculated since the influence of the impinging shock on these regions is small compared with the influence of the bow shock (ref. 1).

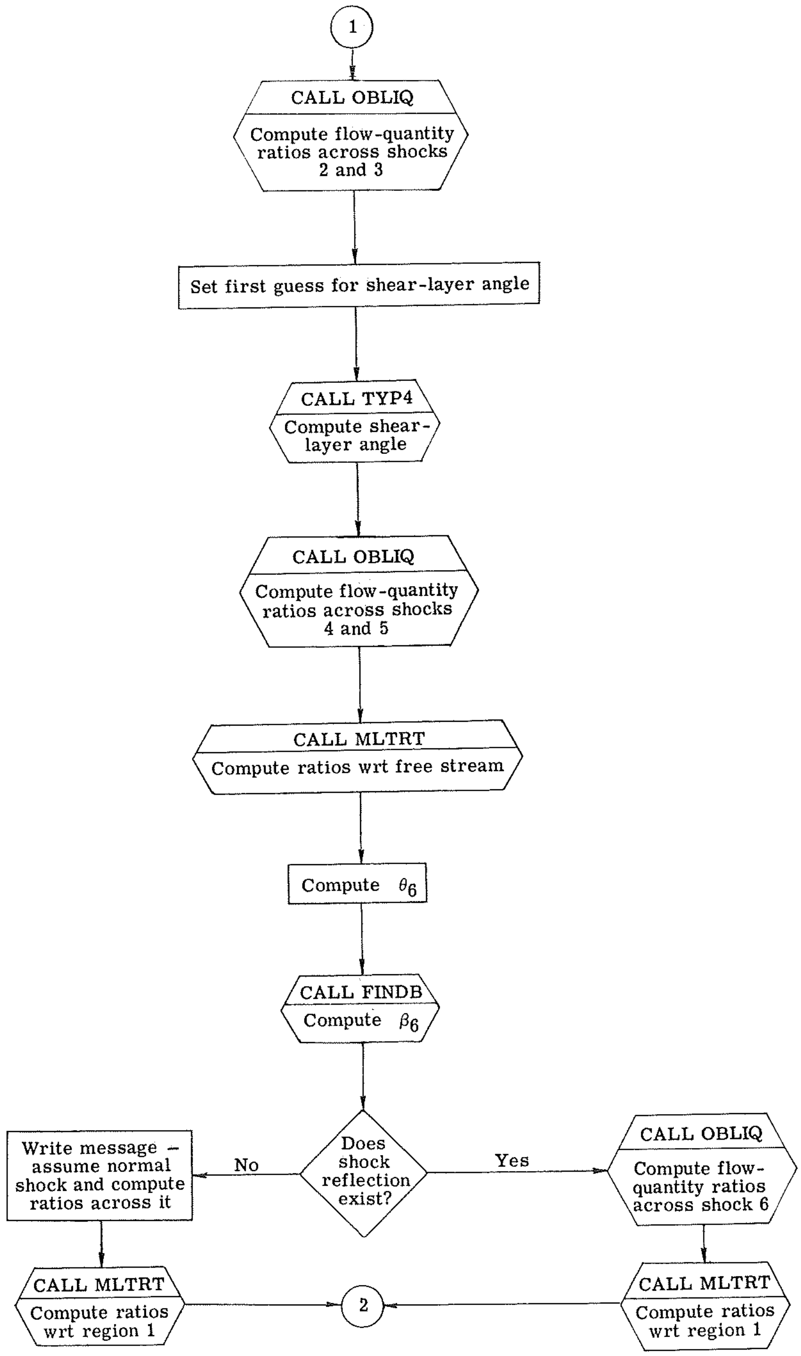
Given the free-stream conditions in region 1 and either the body angle θ_b or bow shock angle β_b, the triple-shock configuration with a shear layer at point A is determined by an iterative procedure similar to that discussed for a type I interference in part I with the exception that strong-shock relations are used between regions 1 and 5. Flow data presented in references 1 and 2 indicate that the shocks and shear layer at point A are nearly straight; therefore, the conditions in region 4 are approximately those calculated by assuming no shock or shear-layer curvature and a nearly normal shock between A and B. When the regular shock reflection between regions 4 and 6 is no longer possible, it is replaced by a Mach reflection and a normal shock is assumed near the wall. Once the pressure rise from region 2 to region 6 is known, the heat-transfer rise is determined with the same procedure as used for type I (eq. (1)). The reference, or undisturbed, heating ahead of the shock—boundary-layer interaction at IP is calculated in the same manner as for type I.

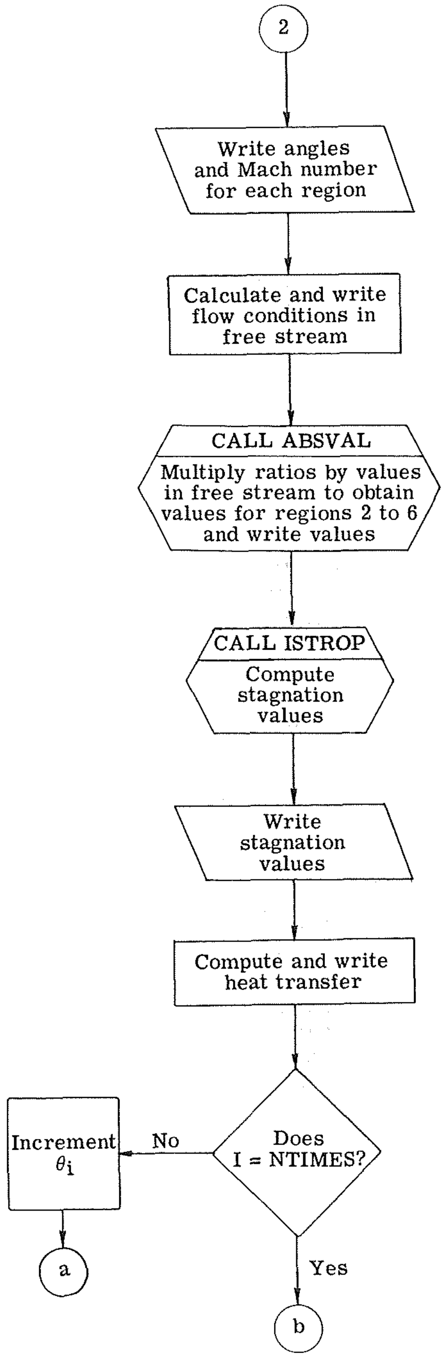
PROGRAM DESCRIPTION

The main program reads the input, calls the various subprograms, and computes the heat transfer. The TYP4 subprogram computes the flow deflection angle of the shear layer at point A (fig. 4). FTHETA is called to compute the flow deflection angle and FINDB is called to compute the shock angles in each region. The subprograms OBLIQ, MLTRT, ABSVAL, and ISTROP compute flow variables and ratios of the flow variables. PINPUT prints input variables. The flow charts and listings of these subprograms are presented in part VII. The flow diagram and listing for the main program are given in the following sections.

Program Flow Chart – Main




1
CALL OBLIQ
Compute flow-quantity ratios across shocks 2 and 3
Set first guess for shear-layer angle
CALL TYP4
Compute shear-layer angle
CALL OBLIQ
Compute flow-quantity ratios across shocks 4 and 5
CALL MLTRT
Compute ratios wrt free stream
Compute θ_6
CALL FINDB
Compute β_6
Does shock reflection exist?
No
Yes
Write message – assume normal shock and compute ratios across it
CALL OBLIQ
Compute flow-quantity ratios across shock 6
CALL MLTRT
Compute ratios wrt region 1
2
CALL MLTRT
Compute ratios wrt region 1


2
Write angles and Mach number for each region
Calculate and write flow conditions in free stream
CALL ABSVAL
Multiply ratios by values in free stream to obtain values for regions 2 to 6 and write values
CALL ISTROP
Compute stagnation values
Write stagnation values
Compute and write heat transfer
Does I = NTIMES?
No
Increment θ_i
a
Yes
b

Program Listing – Main

```
      PROGRAM SHOCK(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C     ..............................................................
C
C     THIS PROGRAM PERFORMS A TYPE II SHOCK INTERFERENCE PATTERN
C     FOR  TWO DIMENSIONAL FLOW
C
C     ..............................................................
      DIMENSION T2STAR(2), RHO2STR(2), V2STAR(2), REY2STR(2), HR(2), QFP
     1(2), HPK(2), QPK(2), STN2(2)
      DIMENSION PN(2)
      DIMENSION AA(2), RN(2)
      DIMENSION STN1(2)
      DIMENSION RR(2), TR(2), HFP(2)
      COMMON  PZ, RHOZ, TZ, P1OPZ, RHO1OZ, T1OTZ,
     1          PZ2, RHOZ2, TZ2, P2OPZ2, RHO2Z2, T2OTZ2,
     2          PZ3, RHOZ3, TZ3, P3OPZ3, RHO3Z3, T3OTZ3,
     3          PZ4, RHOZ4, TZ4, P4OPZ4, RHO4Z4, T4OTZ4,
     4          PZ5, RHOZ5, TZ5, P5OPZ5, RHO5Z5, T5OTZ5,
     5          PZ6, RHOZ6, TZ6, P6OPZ6, RHO6Z6, T6OTZ6,
     6          P2OP1, RHO2O1, T2OT1, A2OA1, U2OU1,
     7          P3OP2, RHO3O2, T3OT2, A3OA2, U3OU2,
     8          P3OP1, RHO3O1, T3OT1, A3OA1, U3OU1,
     9          P4OP2, RHO4O2, T4OT2, A4OA2, U4OU2,
     $          P4OP1, RHO4O1, T4OT1, A4OA1, U4OU1,
     $          P5OP3, RHO5O3, T5OT3, A5OA3, U5OU3,
     $          P6OP2, RHO6O2, T6OT2, A6OA2, U6OU2,
     $          P6OP4, RHO6O4, T6OT4, A6OA4, U6OU4,
     $          P5OP1, RHO5O1, T5OT1, A5OA1, U5OU1,
     $          P6OP1, RHO6O1, T6OT1, A6OA1, U6OU1
      COMMON    P1, RHO1, T1, A1, U1, VISC1, REY1,
     1          P2, RHO2, T2, A2, U2, VISC2, REY2,
     2          P3, RHO3, T3, A3, U3, VISC3, REY3,
     3          P4, RHO4, T4, A4, U4, VISC4, REY4,
     4          P5, RHO5, T5, A5, U5, VISC5, REY5,
     5          P6, RHO6, T6, A6, U6, VISC6, REY6
      NAMELIST /DATAIN/ RM1,GAMMA,THETAB,THETA1,TINCR,NTIMES,IPT,T,P,AMW
     1,TREF,VREF,XL,S,TWALL,CP,PR,RUN,ANGLE,ANGLE2,TOL
C     TOL IS THE CONVERGENCE CRITERION FOR CONDITION 1 AND 2
C     INITIALIZE CONSTANTS
      BETA=4HBETA
      IO=1
      PN(1)=1.29
      PN(2)=0.85
      AA(1)=0.332
      AA(2)=.185
      RN(1)=-.5
      RN(2)=-2.584
C     ..............................................................
C
C     INPUT DATA
C
C     ..............................................................
  101 READ (5,DATAIN)
      IF (ENDFILE 5) 102,103
  102 STOP
```

```
103   CONTINUE
      WRITE(6,DATA IN)
      RR(1)=SQRT(PR)
      RR(2)=PR**(1./3.)
      THBDEG=THETAB
      THIDEG=THETAI
      WRITE (6,120) RUN
C     GAS CONSTANT (FT-LBF/LBM-R)
      R=1544.3/AMW
C     DENSITY (SLUG/CU-FT)
      RHO=P*144./(32.2*R*T)
      IF (IPT) 104,104,105
C     STAGNATION CONDITIONS
104   TZ=T
      RHOZ=RHO
      PZ=P
      GO TO 106
C     FREE STREAM CONDITIONS
105   T1=T
      P1=P
      RHO1=RHO
106   CONTINUE
      CALL ISTROP (GAMMA,RM1,P1,PZ,P1OPZ,IPT)
C     PRINT OUT INPUT VARIABLES
      CALL PINPUT (RM1,GAMMA,IPT,T,P,AMW,TREF,VREF,XL,S,TWALL,CP,PR)
      WRITE (6,121) XL
      ITYP2=0
C               ITYP2 = 0   NORMAL
C                       1   COULD NOT FIND BETA6
C                       2   CALCULATE LAST POINT BEFORE CONDITION 1
C                       3   INCREMENT NORMALLY UNTIL CONDITION 4
C                       4   COULD NOT FIND BETA4 OR BETA5
C                       5   CALCULATE LAST POINT BEFORE CONDITION 4
C     CONVERT ANGLES TO RADIANS
      TINCR=TINCR/57.296
      THETAB=THBDEG/57.296
      THETAI=THETAI/57.296
      INPBB=0
      INPBI=0
C     SAVE THETA AND TINCR TO RESTORE AFTER CONDITION 2
      SINCR=TINCR
      STHETA=THETAI
C     INITIALIZE THFOLD AND THIOLD FOR INITIAL ESTIMATE FOR THETAF
      THFOLD=THETAI+THETAB
      THIOLD=THETAI
C     THIFST SAVES ORIGINAL THETAI IN CASE MULTIPLE THETAB*S ARE READ
      THIFST=THIDEG
      DO 118 I=1,NTIMES
      WRITE (6,125)
      IF (ANGLE.NE.BETA) GO TO 107
C     BETAI WAS INPUT INSTEAD OF THETAI
      BETAI=THETAI
      INPBI=1
      THETAI=FTHETA(GAMMA,RM1,BETAI)
      GO TO 108
107   BETAI=FINDB(GAMMA,RM1,THETAI,1,IERROR)
      IF (IERROR-2) 108,108,110
108   IF (ANGLE2.NE.BETA) GO TO 109
C     BETAB WAS INPUT INSTEAD OF THETAB
      BETAB=THETAB
```

```
      INPBB=1
      THETAB=-FTHETA(GAMMA,RM1,ABS(BETAB))
      GO TO 111
  109 BETAB=-FINDB(GAMMA,RM1,-THETAB,1,IERROR)
      IF (IERROR-2) 111,111,110
  110 WRITE (6,122)
      GO TO 119
  111 THBDEG=THETAB*57.296
      THIDEG=THETAI*57.296
      WRITE (6,123) THIDEG,THBDEG
      WRITE (6,124)
C     ..................................................................
C
C                ERRORS IN FINDING BETA
C                IERROR = 1  ONE SOLUTION WAS FOUND, CONTINUE
C                         2  SOLUTION DID NOT CONVERGE, USE LAST B COMPUTE
C                         3  NO SOLUTION WAS FOUND, START NEW CASE
C                         4  NOT DEFINED
C
C     ..................................................................
      SINBI=SIN(BETAI)
      SINBB=SIN(BETAB)
      BBDEG=BETAB*57.296
      BIDEG=BETAI*57.296
C     FIND RATIOS FOR REGION 2 WITH RESPECT TO REGION 1
      CALL OBLIQ (GAMMA,RM1,THETAB,BETAB,RM2,P2OP1,1,2,IO)
C     FIND RATIOS FOR REGION 3 WITH RESPECT TO REGION 1
      CALL OBLIQ (GAMMA,RM1,THETAI,BETAI,RM3,P3OP1,1,3,IO)
      ISW=0
C     ..................................................................
C
C     CONDITION 1
C     ITERATE ON THETAF UNTIL P4 = P5
C
C     ..................................................................
      DTHETA=.01
      THETAF=0.
      BETA5=1.5708
      CALL TYP4 (THETAF,BETA5,RM1,RM2,ABS(THETAB),THETA4,BETA4,P2OP1,GAM
     1MA,TOL,IERROR)
      BETA5=-BETA5
      THETAF=-THETAF
      THETA5=THETAF
C                                  ITERATION ON P4=P5 IS COMPLETED
C     ..................................................................
C
C     ITERATION ON P4 AND P5 IS COMPLETED. USE COMPUTED THETAF TO CALCUL
C     CONDITIONS 4-6.
C
C     ..................................................................
      SINB4=SIN(BETA4)
      SINB5=SIN(BETA5)
      TFDEG=THETAF*180./3.1416
      THFOLD=THETAF
      THIOLD=THETAI
C     FIND RATIOS FOR REGION 4 WITH RESPECT TO REGION 2
      CALL OBLIQ (GAMMA,RM2,THETA4,BETA4,RM4,P4OP2,2,4,IO)
C     FIND RATIOS FOR REGION 5 WITH RESPECT TO REGION 1
      CALL OBLIQ (GAMMA,RM1,ABS(THETAF),ABS(BETA5),RM5,P5OP1,1,5,IO)
C     FIND RATIOS FOR REGION 4 WITH RESPECT TO REGION 1
      CALL MLTRT (P4OP2,P2OP1,P4OP1,1,4,IO)
```

```
      THETA6=THETAB-THETAF
      BETA6=-FINDB(GAMMA,RM4,ABS(THETA6),1,IERROR)
      IF (IERROR-3) 113,112,113
C     ..................................................................
C
C     CONDITION 2
C     SHOCK REFLECTION NOT POSSIBLE.
C
C     ..................................................................
112   RM2SQ=RM2*RM2
      BETA6=1.5708
      WRITE (6,126)
C     BECAUSE OBLIQUE REFLECTION NOT POSSIBLE BETWEEN 4 AND 6 USE NORMAL
C     SHOCK RELATIONS BETWEEN 6 AND 2
      P6OP2=1.+2.*GAMMA/(GAMMA+1.)*(RM2SQ-1.)
      RHO6O2=(GAMMA+1.)*RM2SQ/((GAMMA-1.)*RM2SQ+2.)
      T6OT2=(2.*GAMMA*RM2SQ-(GAMMA-1.))*((GAMMA-1.)*RM2SQ+2.)
      T6OT2=T6OT2/((GAMMA+1.)**2*RM2SQ)
      A6OA2=ARATIO(T6OT2)
      RM6=SQRT(((GAMMA-1.)*RM2SQ+2.)/(2.*GAMMA*RM2SQ-(GAMMA-1.)))
      U6OU2=A6OA2*RM6/RM2
      WRITE (6,127) P6OP2,RHO6O2,T6OT2,A6OA2,U6OU2
C     FIND RATIOS FOR REGION 6 WITH RESPECT TO REGION 1
      CALL MLTRT (P6OP2,P2OP1,P6OP1,1,6,IO)
      GO TO 114
C     SHOCK REFLECTION POSSIBLE. USE OBLIQUE SHOCK RELATION BETWEEN 6 AN
113   CALL OBLIQ (GAMMA,RM4,ABS(THETA6),ABS(BETA6),RM6,P6OP4,4,6,IO)
      P6OP2=P6OP4*P4OP2
C     FIND RATIOS FOR REGION 6 WITH RESPECT TO REGION 1
      CALL MLTRT (P6OP4,P4OP1,P6OP1,1,6,IO)
C     ..................................................................
C
C     WRITE THETA AND BETA FOR EACH REGION
C
C     ..................................................................
114   WRITE (6,128)
C     WRITE  THETA AND BETA FOR REGION 2
      THFDEG=THETAF*57.296
      THDEG=THBDEG
      BETDEG=BETAB*57.296
      ABSTH=THBDEG
      ABSBT=BETDEG
      J=2
      WRITE (6,129) J,THDEG,BETDEG,ABSTH,ABSBT,RM1,RM2
C     WRITE THETA AND BETA FOR REGION 3
      ABSTH=THIDEG
      ABSBT=BIDEG
      J=3
      WRITE (6,129) J,THIDEG,BIDEG,ABSTH,ABSBT,RM1,RM3
C     WRITE THETA AND BETA FOR REGION 4
      THDEG=THETA4*57.296
      BETDEG=BETA4*57.296
      ABSTH=THFDEG
      ABSBT=BETDEG+THBDEG
      J=4
      WRITE (6,129) J,THDEG,BETDEG,ABSTH,ABSBT,RM2,RM4
C     WRITE THETA AND BETA FOR REGION 5
      THDEG=THETA5*57.296
      BETDEG=BETA5*57.296
      ABSTH=THFDEG
      ABSBT=BETDEG
      J=5
```

```
      WRITE (6,129) J,THDEG,BETDEG,ABSTH,ABSBT,RM3,RM5
C     WRITE THETA AND BETA FOR REGION 6
      THDEG=THETA6*57.296
      BETDEG=BETA6*57.296
      ABSTH=THBDEG
      IF (BETA6.EQ.1.5708) GO TO 115
      ABSBT=BETDEG+THFDEG
      RM=RM4
      GO TO 116
115   ABSBT=BETDEG+THBDEG
      RM=RM2
116   J=6
      WRITE (6,129) J,THDEG,BETDEG,ABSTH,ABSBT,RM,RM6
C     ..................................................................
C
C     CALCULATE AND WRITE PARAMETER VALUES FOR EACH REGION
C
C     ..................................................................
      VISC1=VISCJ(VREF,TREF,T1,S)
      A1=SQRT(32.2*GAMMA*R*T1)
      U1=A1*RM1
      REY1=RHO1*U1/VISC1
      WRITE (6,130)
      WRITE (6,131)
C     WRITE ABSOLUTE VALUES FOR REGION 1
      J=1
      WRITE (6,132) J,P1,RHO1,T1,A1,U1,VISC1,REY1,RM1
C     WRITE ABSOLUTE VALUES FOR REGION 2
      J=2
      CALL ABSVAL (P2OP1,P1,P2,VREF,TREF,S,J,IO,RM2)
C     WRITE ABSOLUTE VALUES FOR REGION 3
      J=3
      CALL ABSVAL (P3OP1,P1,P3,VREF,TREF,S,J,IO,RM3)
C     WRITE ABSOLUTE VALUES FOR REGION 4
      J=4
      CALL ABSVAL (P4OP1,P1,P4,VREF,TREF,S,J,IO,RM4)
C     WRITE ABSOLUTE VALUES FOR REGION 5
      J=5
      CALL ABSVAL (P5OP1,P1,P5,VREF,TREF,S,J,IO,RM5)
C     WRITE ABSOLUTE VALUES FOR REGION 6
      J=6
      CALL ABSVAL (P6OP1,P1,P6,VREF,TREF,S,J,IO,RM6)
C     ..................................................................
C
C     CALCULATE AND WRITE STAGNATION VALUES FOR EACH REGION
C
C     ..................................................................
      WRITE (6,134)
      J=1
      WRITE (6,132) J,PZ,RHOZ,TZ
      J=2
      CALL ISTROP (GAMMA,RM2,P2,PZ2,P2OPZ2,2)
      PZ2OZ=PZ2/PZ
      WRITE (6,133) J,PZ2,RHOZ2,TZ2,PZ2OZ
      J=3
      CALL ISTROP (GAMMA,RM3,P3,PZ3,P3OPZ3,3)
      PZ3OZ=PZ3/PZ
      WRITE (6,133) J,PZ3,RHOZ3,TZ3,PZ3OZ
      J=4
      CALL ISTROP (GAMMA,RM4,P4,PZ4,P4OPZ4,4)
      PZ4OZ=PZ4/PZ
      WRITE (6,133) J,PZ4,RHOZ4,TZ4,PZ4OZ
```

```
      J=5
      CALL ISTROP (GAMMA,RM5,P5,PZ5,P5OPZ5,5)
      PZ5OZ=PZ5/PZ
      WRITE (6,133) J,PZ5,RHOZ5,TZ5,PZ5OZ
      J=6
      CALL ISTROP (GAMMA,RM6,P6,PZ6,P6OPZ6,6)
      PZ6OZ=PZ6/PZ
      WRITE (6,133) J,PZ6,RHOZ6,TZ6,PZ6OZ
C     ..............................................................
C
C     CALCULATE AND WRITE STANTON NUMBER, FLAT PLATE HEAT TRANSFER
C     COEFFICIENT(HFP), AND HEATING RATE(QFP)  IN REGION 2
C
C     ..............................................................
C     J = 1 IS LAMINAR AND J=2 IS TURBULENT
      DO 117 J=1,2
C     RECOVERY TEMPERATURE
      TR(J)=T2+RR(J)*(TZ-T2)
C     ECKERT≠S REFERENCE TEMPERATURE
      T2STAR(J)=.5*(TWALL+T2)+.22*(TR(J)-T2)
      RHO2STR(J)=144.*P2/(32.2*R*T2STAR(J))
      V2STAR(J)=VISCJ(VREF,TREF,T2STAR,S)
      REY2STR(J)=RHO2STR(J)*U2*XL/V2STAR(J)
C     LOCAL STANTON NUMBER IN REGION 2 AT IMPINGEMENT
      CF2=AA(J)*REY2STR**RN(J)
      IF (J.EQ.2) CF2=AA(J)*ALOG10(REY2STR)**RN(J)
      STN2(J)=CF2*PR**(-2./3.)
C     FLAT PLATE HEAT TRANSFER COEF(BTU/SEC-FT2-R)
      HFP(J)=STN2(J)*RHO2STR*U2*CP/778.
C     FREE STREAM STANTON NUMBER
      STN1(J)=778.*HFP(J)/(RHO1*U1*CP)
C     FLAT PLATE HEATING RATE(BTU/SEC-FT2)
      QFP(J)=HFP(J)*(TR(J)-TWALL)
C     MARKARIAN HEAT TRANSFER RATIOS
      HR(J)=P6OP2**PN(J)
C     PEAK HEATING RATE
      QPK(J)=HR(J)*QFP(J)
C     PEAK HEAT TRANSFER COEF
117   HPK(J)=HFP(J)*HR(J)
      WRITE (6,135)
      WRITE (6,136) QFP(1),HFP(1),STN2(1),STN1(1),P6OP2,HR(1),QPK(1),HPK
     1(1)
      WRITE (6,137) QFP(2),HFP(2),STN2(2),STN1(2),P6OP2,HR(2),QPK(2).HPK
     1(2)
      WRITE (6,138)
118   THETAI=THETAI+TINCR
119   CONTINUE
C     RETURN THETAI AND TINCR TO ORIGINAL VALUES
      THETAI=THIFST
      TINCR=SINCR
      GO TO 101
C
120   FORMAT (1H1,9X,49HTHIS PROGRAM PERFORMS A TYPE 2 SHOCK INTERFERENC
     1E,8H PATTERN,//,13H RUN NUMBER  ,F5.2/)
121   FORMAT (16H XL(WALL LENGTH),15X,F15.6,4H  FT)
122   FORMAT (//33H NO SOLUTION - BOW SHOCK DETACHED)
123   FORMAT (1H1,20HINPUT VARIABLES ARE /9H THETAI =,F9.4,19H DEG, AND
     1THETAB = ,F9.4,4H DEG//)
124   FORMAT (//12H RATIOS ARE /)
125   FORMAT (1H /)
126   FORMAT (/1X,43HSHOCK REFLECTION NOT POSSIBLE AT THIS POINT/)
```

```
127   FORMAT (1X,6HP6/P2=,F8.4,5X,7HRHO6/2=,F8.4,5X,6HT6/T2=,F8.4,5X,6HA
     16/A2=,F8.4,5X,6HU6/U2=,F8.4)
128   FORMAT (//7H REGION,5X,14HRELATIVE ANGLE,10X,14HABSOLUTE ANGLE/9X,
     15HTHETA,8X,4HBETA,7X,5HTHETA,8X,4HBETA,29H   UPSTREAM MACH     LOCAL
     2 MACH)
129   FORMAT (1X,I1,4F12.4,2F15.4)
130   FORMAT (//7H REGION,10X,1HP,12X,3HRHO,11X,1HT,11X,1HA,11X,1HU,13X,
     12HMU,3X,11HREYNOLDS NO,9H   MACH NO)
131   FORMAT (14X,3HPSI,4X,10HSLUG/CU FT,5X,7HRANKINE,6X,6HFT/SEC,6X,6HF
     1T/SEC,4X,11HSLUG/FT-SEC,11X,4H1/FT)
132   FORMAT (1X,I5,F12.4,E15.5,3F12.4,2E15.5,F8.4)
133   FORMAT (1X,I5,F12.4,E15.5,3F12.6,2E15.5)
134   FORMAT (/1X,25HSTAGNATION CONDITIONS ARE/7H REGION,6X,5HPSTAG,12X,
     13HRHO,7X,5HTSTAG,4X,12HPSTAG/PSTAG1,/,14X,4HPSIA,4X,11HSLUGS/CU FT
     2,5X,7HRANKINE)
135   FORMAT (//14H HEAT TRANSFER,/17X,1HQ,14X,3HHFP,12X,8HSTANTON2,7X,8
     1HSTANTON1,7X,5HP6/P2,10X,2HHR,12X,3HQPK,12X,3HHPK)
136   FORMAT (8H LAMINAR,2X,8(E15.5))
137   FORMAT (10H TURBULENT,8(E15.5))
138   FORMAT (1H0,41HHFP = HEAT TRANSFER COEF(BTU/SQ FT-SEC-R)/35H Q    =
     1 HEAT TRANSFER(BTU/SQ FT-SEC))
      END
C     ................................................................
C     ................................................................
```

USAGE

Program SHOCK for a type II interference pattern uses the standard FORTRAN NAMELIST input with $DATAIN as the NAMELIST name. The input includes the flow conditions, gas properties, impinging-flow deflection or shock angle, and impingement location on the body. The program has an option to increment the body angle. These input variables should be applied first to the type I program to determine whether the interference is type I or II.

A description of the input and output variables and a sample case are presented.

Input Description

The $DATAIN input for type II is as follows:

RUN	run number for identification
RM1	M_∞, free-stream Mach number
GAMMA	c_p/c_v, ratio of specific heats
THETAI	θ_i, shock generator angle, deg; or β_i, impinging shock angle, deg

THETAB	θ_b, body angle, deg (input as negative angle); or β_b, bow shock angle, deg (input as negative angle)
TINCR	increment for θ_i, deg
NTIMES	number of times to increment θ_i
IPT	initial point; 0 for stagnation conditions, 1 for free-stream static conditions
T	temperature at IPT, $^{\circ}R$
P	pressure at IPT, psia
AMW	molecular weight (used to compute gas constant)
TREF	reference temperature for computing viscosity, $^{\circ}R$
VREF	reference viscosity for computing viscosity, slugs/ft-sec
S	Sutherland's constant in viscosity equation
XL	X_i, distance from leading edge to impingement point, ft
TWALL	temperature at wall, $^{\circ}R$
CP	c_p, specific heat at constant pressure, ft-lbf/slug-$^{\circ}R$
PR	N_{Pr}, Prandtl number
ANGLE	THET if θ_i input; BETA if β_i input
ANGLE2	THET if θ_b input; BETA if β_b input
TOL	acceptable tolerance for equal pressures (0.001)

Output Description

The output is printing only. A heading and pertinent input for identification are printed before the calculations.

RUN NUMBER	run number for identification
M1	M_∞, Mach number in free stream
GAMMA(CP/CV)	ratio of specific heats
TEMP AT POINT "IPT"	input as T, ^oR
PRES AT POINT "IPT"	input as P, psia
MOLECULAR WEIGHT	molecular weight (used to compute gas constant)
REFERENCE TEMP	reference temperature for computing viscosity, ^oR
REFERENCE VISCOSITY	reference viscosity for computing viscosity, slugs/ft-sec
S(SUTHERLAND NUMBER)	Sutherland's constant in viscosity equation
TEMP AT WALL	T_w, ^oR
CP	c_p, specific heat at constant pressure, ft-lbf/slug-^oR
PRANDTL NUMBER	N_{Pr}, Prandtl number
XL(WALL LENGTH)	X_i, length from leading edge to impingement point, ft
THETAI	θ_i, shock generator angle, deg
THETAB	θ_b, body angle, deg
P2/P1, etc.	p_2/p_1, etc., pressure ratios for regions listed
RHO2/1, etc.	ρ_2/ρ_1, etc., density ratios for regions listed

T2/T1, etc.	T_2/T_1, etc., temperature ratios for regions listed
A2/A1, etc.	a_2/a_1, etc., ratios of speeds of sound in regions listed
U2/U1, etc.	u_2/u_1, etc., velocity ratios for regions listed
RELATIVE ANGLE	
THETA	flow angle relative to flow in upstream region, deg
BETA	shock angle relative to flow in upstream region, deg
ABSOLUTE ANGLE	
THETA	flow angle relative to free-stream flow, deg
BETA	shock angle relative to free-stream flow, deg
UPSTREAM MACH	Mach number in upstream region
LOCAL MACH	local Mach number
REGION	region in shock pattern
P	static pressure in region, psia
RHO	static density in region, slugs/ft^3
T	static temperature in region, $^{\circ}$R
A	speed of sound in region, ft/sec
U	velocity in region, ft/sec
MU	static viscosity in region, slugs/ft-sec
REYNOLDS NO	Reynolds number per foot in region

MACH NO	Mach number in region

The following stagnation conditions are then listed:

PSTAG	total pressure in region, psia
RHO	total density in region, slugs/ft^3
TSTAG	total temperature in region, $^{\circ}$R
PSTAG/PSTAG1	ratio of total pressure in region to free-stream total pressure

The pressure ratio and heat transfer for laminar and turbulent flow are listed as

Q	heat-transfer rate, Btu/ft^2-sec
HFP	flat-plate heat-transfer coefficient, Btu/ft^2-sec-$^{\circ}$R
STANTON2	local incompressible Stanton number
STANTON1	compressible free-stream Stanton number
P6/P2	peak pressure ratio
HR	Markarian heat-transfer ratio
QPK	peak heating rate
HPK	peak heat-transfer coefficient

Sample Case – Input

```
$DATAIN
RM1     =  0.6E+01,
GAMMA   =  0.14E+01,
THETAB  = -0.35E+02,
THETAI  =  0.5E+01,
```

```
TINCR   =  0.5E+01,
NTIMES  =  1,
IPT     =  0,
T       =  0.9E+03,
P       =  0.4E+03,
AMW     =  0.2897E+02,
TREF    =  0.53E+03,
VREF    =  0.3801E-06,
XL      =  0.25E+00,
S       =  0.1986E+03,
TWALL   =  0.55E+03,
CP      =  0.6006E+04,
PR      =  0.72E+00,
RUN     =  0.1E+01,
ANGLE   =  0.69404725765109E+93,
ANGLE2  =  0.69404725765109E+93,
TOL     =  0.1E-02,
$END
```

Sample Case – Output

```
        THIS PROGRAM PERFORMS A TYPE 2 SHOCK INTERFERENCE PATTERN

RUN NUMBER    1.00


INPUT VARIABLES ARE

M1                                         6.000
GAMMA(CP/CV)                            1.400000
TEMP AT POINT O                       900.000000   RANKINE
PRES AT POINT O                       400.000000   PSI
MOLECULAR WEIGHT                       28.970000
REFERENCE TEMP                        530.000000   RANKINE
REFERENCE VISCOSITY                 3.801000E-07   SLUG/(FT-SEC)
S(SUTHERLAND NUMBER)                     198.600
TEMP AT WALL                             550.000   RANKINE
CP                                      6006.000   FT-LBF/(SLUG-RANKINE)
PRANDTL NUMBER                           .720000
XL(WALL LENGTH)                          .250000   FT
```

INPUT VARIABLES ARE
THETAI = 5.0000 DEG, AND THETAB = -35.0000 DEG

RATIOS ARE

P2/P1=	23.0772	RHO2/1=	4.7963	T2/T1=	4.8114	A2/A1=	2.1935	U2/U1=	.6860
P3/P1=	2.0103	RHO3/1=	1.6306	T3/T1=	1.2328	A3/A1=	1.1103	U3/U1=	.9837
P4/P2=	1.7913	RHO4/2=	1.5078	T4/T2=	1.1880	A4/A2=	1.0900	U4/U2=	.8562
P5/P1=	41.3370	RHO5/1=	5.2606	T5/T1=	7.8578	A5/A1=	2.8032	U5/U1=	.2180
P4/P1=	41.3371	RHO4/1=	7.2318	T4/T1=	5.7160	A4/A1=	2.3908	U4/U1=	.5874
P6/P4=	1.9068	RHO6/4=	1.5734	T6/T4=	1.2119	A6/A4=	1.1008	U6/U4=	.7159
P6/P1=	78.8202	RHO6/1=	11.3786	T6/T1=	6.9271	A6/A1=	2.6319	U6/U1=	.4205

REGION	RELATIVE ANGLE		ABSOLUTE ANGLE		UPSTREAM MACH	LOCAL MACH
	THETA	BETA	THETA	BETA		
2	-35.0000	-48.0670	-35.0000	-48.0670	6.0000	1.8765
3	5.0000	13.1598	5.0000	13.1598	6.0000	5.3157
4	11.3299	43.6580	-23.6701	8.6580	1.8765	1.4741
5	-23.6701	-83.7595	-23.6701	-83.7595	5.3157	.4666
6	-11.3299	-64.7425	-35.0000	-88.4127	1.4741	.9585

REGION	P	RHO	T	A	U	MU	REYNOLDS NO	MACH NO
	PSI	SLUG/CU FT	RANKINE	FT/SEC	FT/SEC	SLUG/FT-SEC	1/FT	
1	.2533	1.93645E-04	109.7561	513.5679	3081.4074	8.46377E-08	7.05004E+06	6.0000
2	5.8465	9.28781E-04	528.0852	1126.5113	2113.9285	3.79038E-07	5.17989E+06	1.8765
3	.5093	3.15760E-04	135.3111	570.2302	3031.1919	1.06990E-07	8.94597E+06	5.3157
4	10.4725	1.40040E-03	627.3680	1227.8483	1809.9101	4.31811E-07	5.86970E+06	1.4741
5	10.4725	1.01869E-03	862.4436	1439.6234	671.7546	5.41796E-07	1.26304E+06	.4666
6	19.9687	2.20341E-03	760.2870	1351.6752	1295.6479	4.96218E-07	5.75321E+06	.9585

STAGNATION CONDITIONS ARE

REGION	PSTAG	RHO	TSTAG	PSTAG/PSTAG1
	PSIA	SLUGS/CU FT	RANKINE	
1	400.0000	3.72856E-02	900.0000	
2	37.7814	3.52176E-03	900.000039	.094454
3	386.5123	3.60280E-02	900.008771	.966281
4	37.0316	3.45186E-03	900.000057	.092579
5	12.1574	1.13324E-03	899.999987	.030394
6	36.0393	3.35937E-03	900.000056	.090098

HEAT TRANSFER

	Q	HFP	STANTON2	STANTON1	P6/P2	HR	QPK	HPK
LAMINAR	1.58922E+00	5.41165E-03	4.11392E-04	1.17481E-03	3.41551E+00	4.87705E+00	7.75069E+00	2.63929E-02
TURBULENT	9.18804E+00	2.95032E-02	2.24282E-03	6.40483E-03	3.41551E+00	2.84078E+00	2.61012E+01	8.38120E-02

HFP = HEAT TRANSFER COEF(BTU/SQ FT-SEC-R)
Q = HEAT TRANSFER(BTU/SQ FT-SEC)

PART III - TYPE III INTERFERENCE

PROBLEM DISCUSSION

A type III shock-interference pattern occurs when a weak impinging shock intersects a strong detached bow shock, as illustrated in figure 1(c). The shear layer emanating from the shock intersection attaches to the surface with subsonic flow above the shear layer turning upward and supersonic flow below the layer passing through an oblique shock in order to turn parallel with the surface. On a blunt body the shock intersection occurs near or above the lower sonic point, as shown in figure 2.

Once the flow conditions in region 1 and either the angle θ_i or β_i are specified, the triple-shock configuration at point A shown in figure 5 is solved by using an iterative procedure similar to that discussed for type I. The iterative procedure for type III differs in that the strong-shock solutions of the Rankine-Hugoniot equations are used in going from region 1 to region 2. The reflected shock at the attachment point C intersects the transmitted bow shock at point B and results in another triple shock. The analysis thus far is exact. Results from this analysis are used in the following approximate analytic technique to determine the peak pressure and heat transfer at the shear-layer attachment point. The reflected-shock angle at point C is obtained once the flow deflection angle $\bar{\theta}_5$ is specified. The reflected-shock angle and wall pressure (peak pressure) in region 5 are obtained from the Rankine-Hugoniot relations for attachment on a two-dimensional body. For attachment on a body of revolution, tangent-cone approximations (ref. 9) are used to determine the shock angle and wall pressure. In the present analysis, the flow model consists of a plane shock intersecting the bow shock of a sphere in the vertical plane of symmetry.

Peak heating at the wall is caused by the attaching shear layer, which is similar to the case of a reattaching shear layer in a separation region. Correlations proposed by Bushnell and Weinstein (ref. 3) for reattachment heating on two-dimensional ramps are used. The peak heat transfer at attachment is

$$Q_{pk} = A\rho_w u_5 c_p \left(T_{aw} - T_w\right)\left(\frac{\mu_w \sin \bar{\theta}_5}{\rho_w u_5 \delta_{SL}}\right)^N \tag{2}$$

where u_5 is the velocity in region 5, the subscript w indicates wall values, and δ_{SL} is the shear-layer thickness at attachment. The constants A and N (from data in ref. 3) are 0.19 and 0.5 for a laminar shear-layer reattachment, and 0.021 and 0.2 for a turbulent interaction. For the present case (ref. 2) the attachment angles are higher than those of reference 3 and the attachment is three dimensional in nature. Therefore, values of A obtained from correlations of peak-heating data for free shear layers reported in references 2 and 10 are used (0.40 for laminar and 0.06 for turbulent interactions).

The shear-layer thickness at attachment is obtained from the following expressions in reference 3:

Laminar,

$$\delta_{SL} = 5.0\left(\frac{l_{SL}\mu_4}{\rho_4 u_4}\right)^{0.5} \tag{3}$$

Turbulent,

$$\delta_{SL} = 0.123 l_{SL} \tag{4}$$

where l_{SL} is the length of the shear layer from A to C in figure 5. The shear-layer length is determined from the geometry of the triangle ABC formed by the shock and the shear layer and from the shock length AB (or L_{SH}), which must be obtained experimentally or from some approximate method. Shear-layer transition data discussed in reference 11 are useful in determining the state of the shear layer at attachment.

The reference heating used is the stagnation-point value on a sphere obtained from reference 12:

$$Q_{stag} = 0.76\left(N_{Pr}\right)^{-0.6} c_p\left(\rho_w \mu_w\right)^{0.1}\left(\rho_{stag}\mu_{stag}\right)^{0.4}\left(T_{stag} - T_w\right)\sqrt{\left(\frac{du_w}{ds}\right)_{stag}} \tag{5}$$

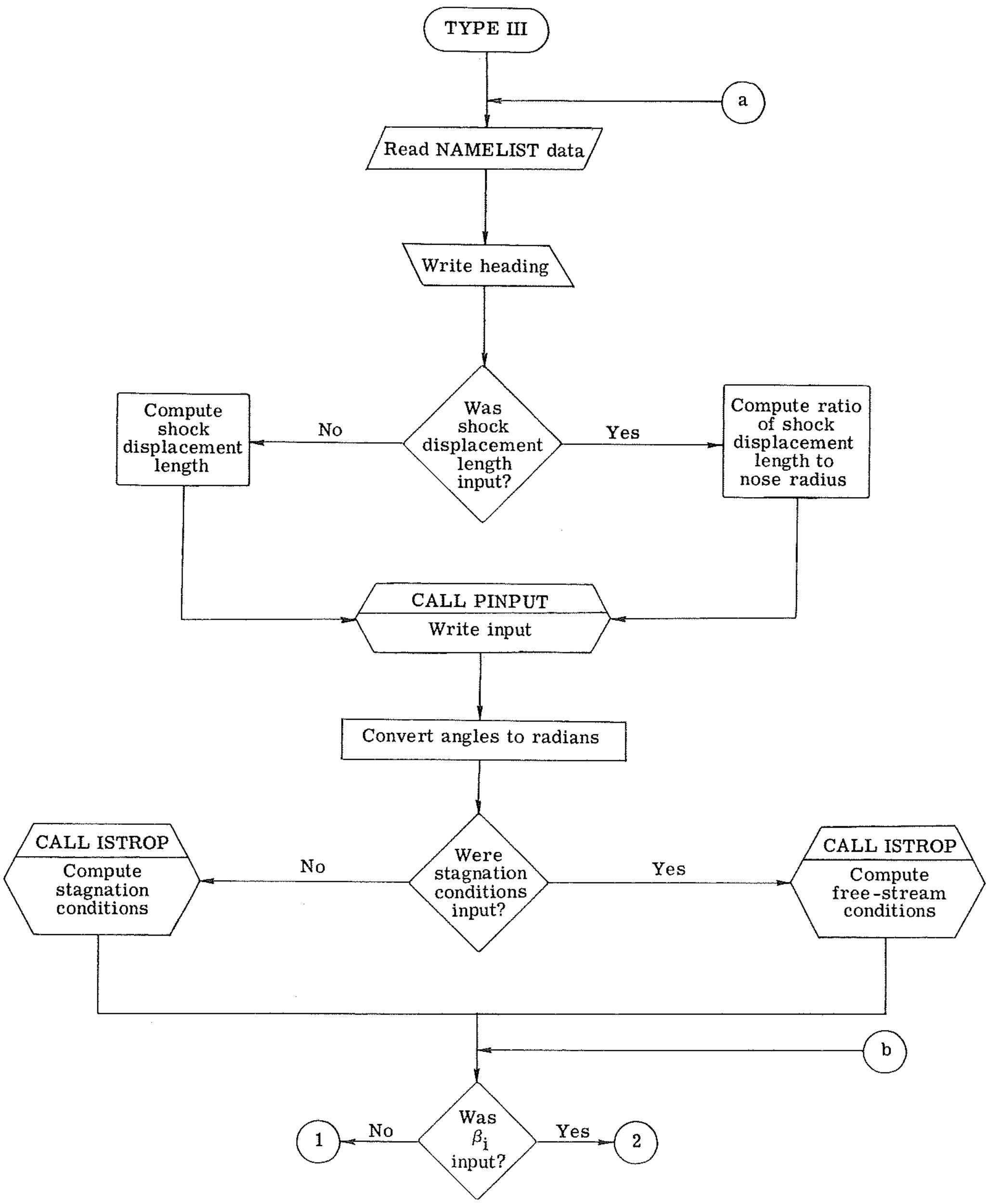
where (from ref. 13)

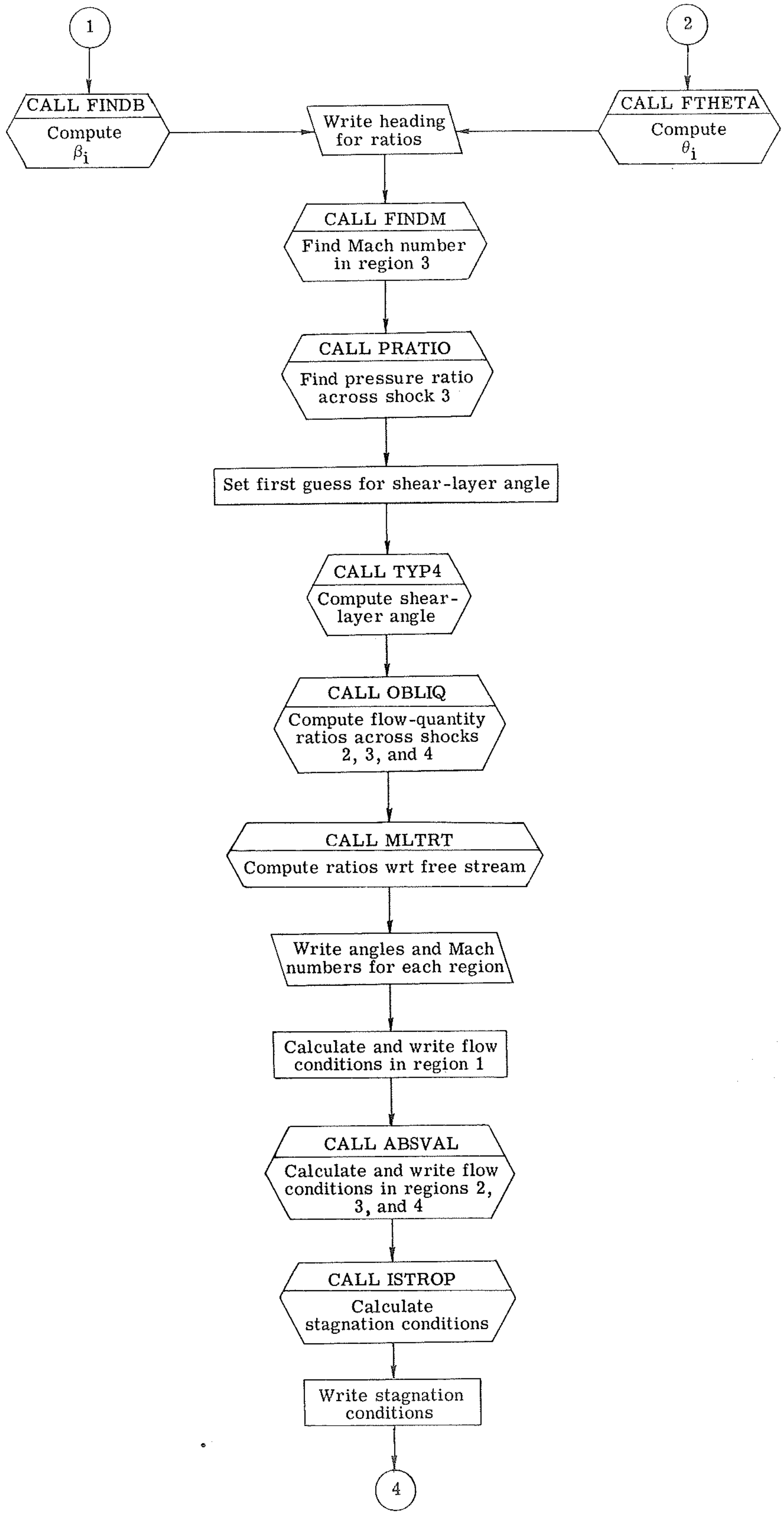
$$\left(\frac{du_w}{ds}\right)_{stag} = \frac{u_\infty}{R_b}\left\{\left(\frac{\gamma - 1}{\gamma}\right)\left[1 + \frac{2}{(\gamma - 1)M_\infty^2}\right]\left(1 - \frac{1}{\gamma M_\infty^2}\right)\right\}^{0.5} \tag{6}$$

PROGRAM DESCRIPTION

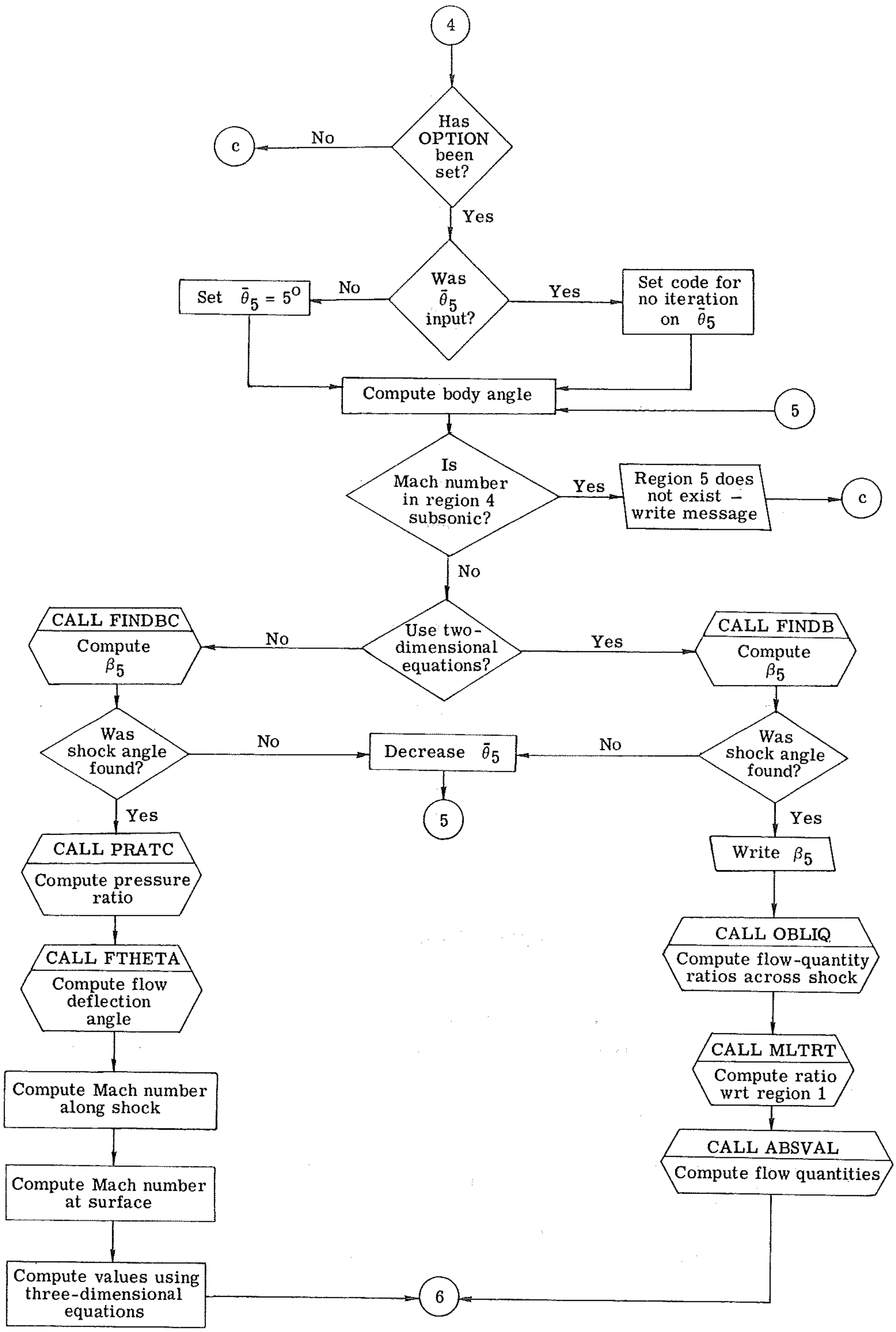
The main program reads the input, calls the various subprograms, and computes the heat transfer. TYP4 computes the flow deflection angle of the shear layer. FTHETA is called to compute the flow angle and FINDB is called to compute the shock angles in each region. The subprograms OBLIQ, FINDM, PRATIO, MLTRT, ABSVAL, AND ISTROP compute flow variables and ratios of the flow variables. PINPUT prints the input variables. The flow charts and listings of these subprograms are presented in part VII. For the axisymmetric option, FINDBC computes the conical shock angle at the shear-layer attachment and PRATC computes the ratio of the pressure at the wall to the static pressure upstream of the conical shock by use of a tangent-cone approximation. The flow diagrams and listings for the main program, PRATC, and FINDBC follow.

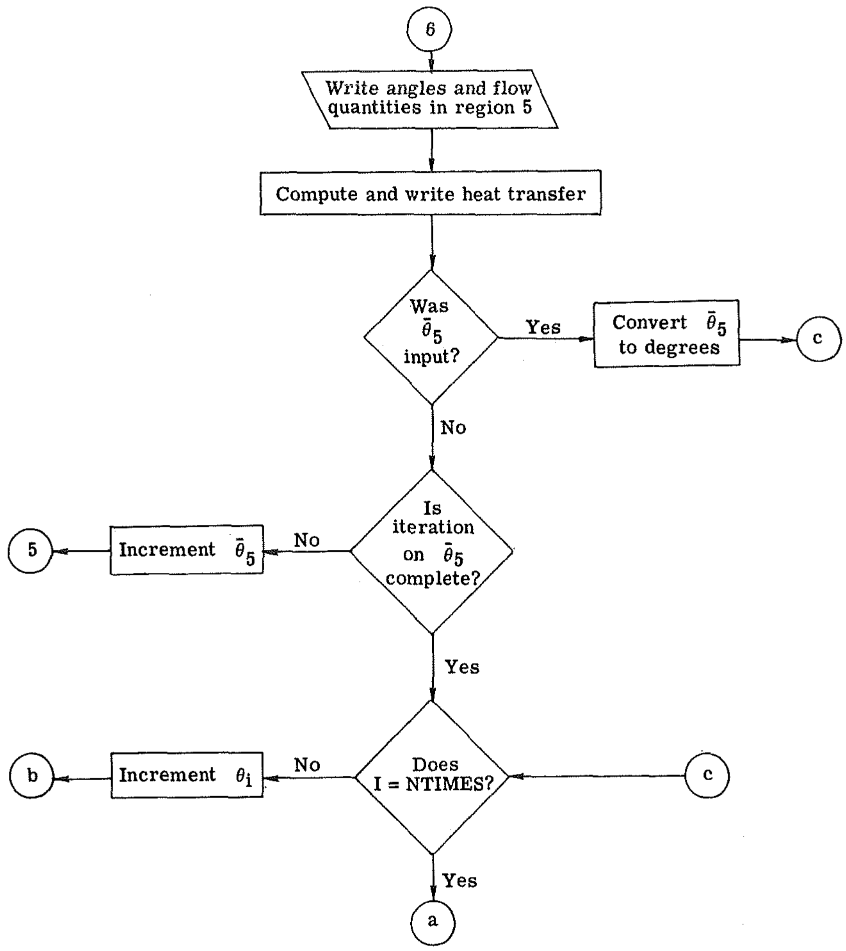
Program Flow Chart – Main





1
CALL FINDB
Compute
β_i
2
CALL FTHETA
Compute
θ_i
Write heading for ratios
CALL FINDM
Find Mach number in region 3
CALL PRATIO
Find pressure ratio across shock 3
Set first guess for shear-layer angle
CALL TYP4
Compute shear-layer angle
CALL OBLIQ
Compute flow-quantity ratios across shocks 2, 3, and 4
CALL MLTRT
Compute ratios wrt free stream
Write angles and Mach numbers for each region
Calculate and write flow conditions in region 1
CALL ABSVAL
Calculate and write flow conditions in regions 2, 3, and 4
CALL ISTROP
Calculate stagnation conditions
Write stagnation conditions
4


4
Has OPTION been set?
No
c
Yes
Was $\bar{\theta}_5$ input?
No
Set $\bar{\theta}_5 = 5^o$
Yes
Set code for no iteration on $\bar{\theta}_5$
Compute body angle
5
Is Mach number in region 4 subsonic?
Yes
Region 5 does not exist – write message
c
No
Use two-dimensional equations?
No
CALL FINDBC
Compute β_5
Yes
CALL FINDB
Compute β_5
Was shock angle found?
No
Decrease $\bar{\theta}_5$
5
No
Was shock angle found?
Yes
CALL PRATC
Compute pressure ratio
CALL FTHETA
Compute flow deflection angle
Compute Mach number along shock
Compute Mach number at surface
Compute values using three-dimensional equations
6
Yes
Write β_5
CALL OBLIQ
Compute flow-quantity ratios across shock
CALL MLTRT
Compute ratio wrt region 1
CALL ABSVAL
Compute flow quantities



Program Listing – Main

```
      PROGRAM SHOCK(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C     ..................................................................
C
C     PURPOSE
C     THIS PROGRAM PERFORMS A TYPE III SHOCK INTERFERENCE PATTERN
C
C     ..................................................................
      COMMON  PZ, RHOZ, TZ, P1OPZ, RHO1OZ, T1OTZ,
     1        PZ2, RHOZ2, TZ2, P2OPZ2, RHO2Z2, T2OTZ2,
     2        PZ3, RHOZ3, TZ3, P3OPZ3, RHO3Z3, T3OTZ3,
     3        PZ4, RHOZ4, TZ4, P4OPZ4, RHO4Z4, T4OTZ4,
     4        PZ5, RHOZ5, TZ5, P5OPZ5, RHO5Z5, T5OTZ5,
     5        P2OP1, RHO2O1, T2OT1, A2OA1, U2OU1,
```

```
     6         P3OP1, RHO3O1, T3OT1, A3OA1, U3OU1,
     7         P4OP3, RHO4O3, T4OT3, A4OA3, U4OU3,
     8         P4OP1, RHO4O1, T4OT1, A4OA1, U4OU1,
     9         P5OP4, RHO5O4, T5OT4, A5OA4, U5OU4,
     $         P5OP1, RHO5O1, T5OT1, A5OA1, U5OU1,
     $         P1, RHO1, T1, A1, U1, VISC1, REY1,
     $         P2, RHO2, T2, A2, U2, VISC2, REY2,
     $         P3, RHO3, T3, A3, U3, VISC3, REY3,
     $         P4, RHO4, T4, A4, U4, VISC4, REY4,
     $         P5, RHO5, T5, A5, U5, VISC5, REY5
      DIMENSION RAT(30)
      DIMENSION VALU1(7), VALUZ(7), RATIO(7), VALUJ(7)
      DIMENSION DELTA(2), CHWALL(2), TR(2), QRATE(2)
C     SET DEFAULTS FOR INPUT VARIABLES
      DATA GAMMA/1.4/,SVINC/5.0/,NTIMES/1/,IPT/0/,AMW/28.97/
      DATA THSVI/0./,BTSVI/0./
      DATA TREF/532.98/,VREF/.3807E-6/,RB/1.0/,S/216./,TWALL/530./
      DATA XL/1.0/,CP/6006./,PR/.72/
      DATA ANGLE/4HTHET/,TOL/.001/
      DATA XLRB/0./
      DATA BETA/4HBETA/
      DATA CODE/4HAXIS/,CODE1/4HNONE/
      DATA THETA5/0./,CKTH5/0/,RUN/1./
      NAMELIST /DATAIN/ RM1,GAMMA,THETAI,TINCR,NTIMES,IPT,T,P,AMW,TREF,V
     1REF,RB,S,TWALL,XL,CP,PR,OPTION,TOL,ANGLE,XLRB,THETA5,CKTH5,RUN
C     ..................................................................
C
C     INPUT DATA
C
C     ..................................................................
101   TINCR=SVINC
      THETAI=THSVI
      BETAI=BTSVI
      XLRB=0.
      IO=1
      READ (5,DATAIN)
      IF (ENDFILE 5) 102,103
102   STOP
103   CONTINUE
      WRITE(6,DATAIN)
      WRITE (6,125) RUN
      THSVI=THETAI
      BTSVI=BETAI
      SVINC=TINCR
      IF (XLRB.NE.0.) GO TO 104
      XLRB=XL/RB
      GO TO 105
104   XL=XLRB*RB
105   CONTINUE
      XL12=XL
C     GAS CONSTANT(FT-LBF/LBM-R)
      R=1544.3/AMW
C     DENSITY  (SLUG/(CU FT)
      RHO=P*144./(32.2*R*T)
      CALL PINPUT (RM1,GAMMA,IPT,T,P,AMW,TREF,VREF,XL,S,TWALL,CP,PR)
      WRITE (6,126) XL12
      WRITE (6,127) RB
      WRITE (6,128) OPTION
      INPB=0
      TINCR=TINCR/57.296
      THETAI=THETAI/57.296
      BETAI=BETAI/57.296
```

```
      THETAI=THETAI-TINCR
      BETAI=BETAI-TINCR
      IF (IPT) 106,106,107
106   TZ=T
      RHOZ=RHO
      PZ=P
      GO TO 108
107   T1=T
      RHO1=RHO
      P1=P
108   CONTINUE
      CALL ISTROP (GAMMA,RM1,P1,PZ,P1OPZ,IPT)
      DO 124 I=1,NTIMES
      ISW=0
      IF (ANGLE.NE.BETA) GO TO 109
C     BETAI WAS INPUT INSTEAD OF THETAI
      INPB=1
      BETAI=BETAI+TINCR
      THETAI=FTHETA(GAMMA,RM1,BETAI)
      GO TO 111
109   THETAI=THETAI+TINCR
      BETAI=FINDB(GAMMA,RM1,THETAI,1,IERROR)
      IF (IERROR-2) 111,111,110
110   GO TO (101,101,101,101), IERROR
C                                ERRORS IN FINDING BETA
C               IERROR = 1 ONE SOLUTION WAS FOUND, CONTINUE
C                        2 SOLUTION DID NOT CONVERGE, USE LAST BETA COMPU
C                        3 NO SOLUTION WAS FOUND, START NEW CASE
C                        4 NOT DEFINED
111   BIDEG=BETAI*180./3.1416
      THIDEG=THETAI*180./3.1416
      WRITE (6,129)
      WRITE (6,130) THIDEG,BIDEG
C     .................................................................
C
C     ITERATE ON THETAF UNTIL P2 = P4
C
C     .................................................................
      THETAF=0.
      BETA2=1.5708
      RM3=FINDM(GAMMA,RM1,SIN(BETAI),BETAI,THETAI)
      P3OP1=PRATIO(GAMMA,RM1,SIN(BETAI))
C               A TYPE 4 INTERFERENCE PATTERN WITH INITIAL MACH NO RM1
C               ENTERING AT ANGLE 0 DEGREES
      CALL TYP4 (THETAF,BETA2,RM1,RM3,THETAI,THETA4,BETA4,P3OP1,GAMMA,TO
     1L,IERROR)
      IF (IERROR-3) 112,101,101
C     .................................................................
C
C     CALCULATE AND WRITE PARAMETER RATIOS FOR 2/1, 4/3, 4/1
C
C     .................................................................
112   WRITE (6,131)
      IO=1
      CALL OBLIQ (GAMMA,RM1,ABS(THETAF),BETA2,RM2,P2OP1,1,2,IO)
      CALL OBLIQ (GAMMA,RM1,THETAI,BETAI,RM3,P3OP1,1,3,IO)
      CALL OBLIQ (GAMMA,RM3,THETA4,BETA4,RM4,P4OP3,3,4,IO)
      CALL MLTRT (P4OP3,P3OP1,P4OP1,1,4,IO)
C               WRITE THETA AND BETA ANGLES AND MACH NUMBER
      WRITE (6,132)
      THEDEG=THETAF*57.296
```

```
      IF (THETAF.LT.0.) BETA2=3.14159-BETA2
      BETDEG=BETA2*57.296
      J=2
      WRITE (6,133) J,THFDEG,BETDEG,THFDEG,BETDEG,RM1,RM2
      THDEG=THETAI*57.296
      BETDEG=BETAI*57.296
      J=3
      WRITE (6,133) J,THDEG,BETDEG,THDEG,BETDEG,RM1,RM3
      THDEG=-THETA4*57.296
      BETDEG=-BETA4*57.296
      ABSTH=THFDEG
      ABSBT=THDEG+BETDEG
      J=4
      WRITE (6,133) J,THDEG,BETDEG,ABSTH,ABSBT,RM3,RM4
C     ..............................................................
C
C     CALCULATE ABSOLUTE VALUES FOR POINTS 0 THRU 4
C
C     ..............................................................
      WRITE (6,134)
      WRITE (6,135)
      VISC1=VISCJ(VREF,TREF,T1,S)
      A1=SQRT(32.2*GAMMA*R*T1)
      U1=A1*RM1
      REY1=RHO1*U1/VISC1
      J=1
      WRITE (6,136) J,P1,RHO1,T1,A1,U1,VISC1,REY1,RM1
      J=2
      CALL ABSVAL (P2OP1,P1,P2,VREF,TREF,S,J,IO,RM2)
      J=3
      CALL ABSVAL (P3OP1,P1,P3,VREF,TREF,S,J,IO,RM3)
      J=4
      CALL ABSVAL (P4OP1,P1,P4,VREF,TREF,S,J,IO,RM4)
      WRITE (6,137)
      J=1
      WRITE (6,136) J,PZ,RHOZ,TZ
      J=2
      CALL ISTROP (GAMMA,RM2,P2,PZ2,P2OPZ2,2)
      PZ2OZ=PZ2/PZ
      WRITE (6,136) J,PZ2,RHOZ2,TZ2,PZ2OZ
      J=3
      CALL ISTROP (GAMMA,RM3,P3,PZ3,P3OPZ3,3)
      PZ3OZ=PZ3/PZ
      WRITE (6,136) J,PZ3,RHOZ3,TZ3,PZ3OZ
      J=4
      CALL ISTROP (GAMMA,RM4,P4,PZ4,P4OPZ4,4)
      PZ4OZ=PZ4/PZ
      WRITE (6,136) J,PZ4,RHOZ4,TZ4,PZ4OZ
      IF (OPTION.EQ.CODE1) GO TO 124
C     ..............................................................
C
C     CONDITION 1
C     INCREMENT THETA 5 UNTIL REFLECTION AT PT 5 NOT POSSIBLE AT WHICH
C     TIME REFINE THETA5 TO FIND MORE PRECISELY WHEN THIS OCCURS
C
C     ..............................................................
      IF (CKTH5.EQ.0) GO TO 113
      DTHETA=THETA5/57.296
      THETA5=DTHETA
      ISW=1
      GO TO 114
113   DTHETA=5.0/57.296
```

```
      THETA5=DTHETA
      ISW=0
  114 THDEG=-THETA5*180./3.1416
      THETAB=THETAF-THETA5
      THBDEG= THETAB*180./3.1416
      WRITE (6,129)
      IF (RM4.LE.1.) WRITE (6,138)
      IF (RM4.LE.1.) GO TO 124
      WRITE (6,139)
      IF (OPTION.NE.CODE) GO TO 115
C     .................................................................
C
C     AXISYMMETRIC CASE. THETA5,RM5,P5OP4 ARE INPUT
C
C     .................................................................
      WRITE (6,140)
      BETA5=FINDBC(RM4,GAMMA,THETA5,IERROR)
      IF (IERROR.GT.2) GO TO 123
C     PRESSURE RATIO AT SURFACE
      P5OP4=PRATC(RM4,GAMMA,THETA5)
      THETA=FTHETA(GAMMA,RM4,BETA5)
C     MACH NUMBER ALONG SHOCK
      RMSQ=FINDM(GAMMA,RM4,SIN(BETA5),BETA5,THETA)**2
      GM1H=(GAMMA-1.)/2.
      P5P4=PRATIO(GAMMA,RM4,SIN(BETA5))
      P5SP5=P5OP4/P5P4
C     MACH NUMBER AT SURFACE
      RM5=SQRT((P5SP5**(-GM1H)*(1.+GM1H*RMSQ)-1.)/GM1H)
      T5OTZ5=1./(1.+(GAMMA-1.)*RM5**2/2.)
      T5=TZ*T5OTZ5
      P5=P4*P5OP4
      RHO5=P5*144./(32.2*R*T5)
      VISC5=VISCJ(VREF,TREF,T5,S)
      A5=SQRT(32.2*GAMMA*R*T5)
      U5=A5*RM5
      REY5=RHO5*U5/VISC5
      GO TO 117
C     .................................................................
C
C     TWO-DIMENSIONAL CASE.
C     CALCULATE AND WRITE PARAMETER RATIOS FOR 5/4, 5/1
C
C     .................................................................
  115 BETA5=FINDB(GAMMA,RM4,THETA5,1,IERROR)
      IF (IERROR-3) 116,121,121
  116 BETDEG=BETA5*180./3.1416
      THSV=THETA5
      WRITE (6,141) BETDEG
      IO=-1
      CALL OBLIQ (GAMMA,RM4,THETA5,BETA5,RM5,P5OP4,4,5,IO)
      CALL MLTRT (P5OP4,P4OP1,P5OP1,1,5,IO)
C              CALCULATE ABSOLUTE VALUES AT 5
      CALL ABSVAL (P5OP1,P1,P5,VREF,TREF,S,5,-1)
  117 BETDEG=-BETA5*57.296
      BBDEG= (THETAF-BETA5)*57.296
      WRITE (6,142) THDEG,THBDEG,BETDEG,BBDEG
      WRITE (6,143) P5OP4
      WRITE (6,144) P5,RHO5,T5,A5,U5,VISC5,REY5,RM5
C     .................................................................
```

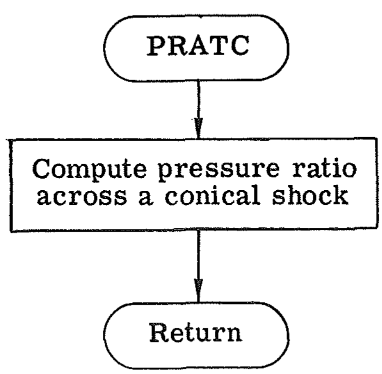
```
C
C     CALCULATE AND WRITE STANTON NUMBER,HEAT TRANSFER COEFFICIENT(H),
C     HEATING RATE(QRATE), AND  SHEAR   LAYER THICKNESS(DELTA) FOR
C     LAMINAR AND TURBULENT FLOW.
C
C     ..............................................................
C     VISCOSITY AT WALL (SLUG/FT-SEC)
      VWALL=VISCJ(VREF,TREF,TWALL,S)
C     DENSITY AT WALL (SLUG/FT CUBE)
      RHOW=P5*144./(32.2*R*TWALL)
      WRITE (6,145) RHOW,VWALL
      WRITE (6,146)
C     SHEAR LAYER LENGTH(FEET)
      XL13=XL12*COS(BETA4-THETA4)-XL12*SIN(BETA4-THETA4)/TAN(BETA5)
C      SHEAR LAYER THICKNESS AT WALL(FT)
      DELTA(1)=5.0*SQRT(XL13*VISC4/(RHO4*U4))
      DELTA(2)=1.6*XL13/13.
C     STANTON NUMBER IN REGION 5
      CH=RHOW*U5/(VWALL*SIN(THETA5))
      CHWALL(1)=.19/(CH*DELTA(1))**.5
      CHWALL(2)=.021/(CH*DELTA(2))**.2
C     RECOVERY TEMPERATURE (DEG-R)
      TR(1)=T5+(TZ-T5)*SQRT(PR)
      TR(2)=T5+(TZ-T5)*(PR**(1./3.))
C     HEAT FLOW(BTU/FT2-SEC)
      QR=RHOW*U5*CP/778.
      QRATE(1)=QR*(TR(1)-TWALL)*CHWALL(1)
      QRATE(2)=QR*(TR(2)-TWALL)*CHWALL(2)
      H1=QR*CHWALL(1)
      H2=QR*CHWALL(2)
C     FIND HEAT TRANSFER FOR A BLUNT BODY WITH NO IMPINGING SHOCK
C
      GM1=GAMMA-1.
      GP1=GAMMA+1.
      TZ5=TZ
C     VISCOSITY AT STAGNATION COND IN REGION 5(SLUG/FT-SEC)
      V5S=VISCJ(VREF,TREF,TZ5,S)
C     CONVERSION FACTOR ( (BTU-SEC2)/(FT2-LBF) )
      AQ=(.76/PR**(.6))/(778.*SQRT(32.2))
C     DELTA HEAT BETWEEN TWALL AND TZ5(FT-LBF/SLUG)
      DQ=CP*(TZ5-TWALL)
      RM1SQ=RM1*RM1
C     CALC STAGNATION PRESSURE RATIO ACROSS A NORMAL SHOCK FOR FREE
C     STREAM CONDITIONS
      TY=(GP1*RM1SQ)/(GM1*RM1SQ+2.)
      TX=GP1/(2.*GAMMA*RM1SQ-GM1)
      PZS=PZ*TY**(GAMMA/GM1)*TX**(1./GM1)
      BQS=((144.*VWALL)/(R*TWALL))**(.1)
      CQS=((144.*V5S)/(R*TZ5))**(.4)
C     STAGNATION VELOCITY GRADIENT
      UGRDTS=U1/RB*SQRT(GM1/GAMMA*(1.+2./(GM1*RM1SQ))*(1.-1./(GAMMA*RM1S
     1Q)))
C     STAGNATION HEATING-3D(BTU/FT2-SEC)
      QWS3D=AQ*BQS*CQS*DQ*SQRT(PZS*UGRDTS)
C     Q-PEAK RATIOS
      QR3DL=QRATE(1)/QWS3D
      QR3DT=QRATE(2)/QWS3D
C     STAGNATION HEAT TRANSFER COEF(BTU/SQFT-SEC-R)
      HS3=QWS3D/(TZ5-TWALL)
C     H-PEAK RATIOS
      H1HS3=H1/HS3
      H2HS3=H2/HS3
```

```
C     PEAK PRESSURE RATIO
      P5OPZS=P5/PZS
      WRITE (6,147) P5OPZS
      WRITE (6,148) XL13
      WRITE (6,149) QWS3D,HS3
      WRITE (6,150)
      WRITE (6,151) CHWALL(1),QRATE(1),DELTA(1),QR3DL,H1HS3,CHWALL(2),QR
     1ATE(2),DELTA(2),QR3DT,H2HS3
C     ARE WE ITERATING ON THETA5 TO FIND PT AT WHICH CONDITION 1 OCCURS
C     IF NOT, CONTINUE INCREMENTING THETA5.
      IF (CKTH5.NE.0.) THETA5=THETA5*57.296
      IF (ISW) 119,119,118
118   GO TO 124
119   THETA5=THETA5+DTHETA
      GO TO 114
C     ..............................................................
C
C
C                 ITERATE ON THETA5
C
C     ..............................................................
120   BETA5=FINDB(GAMMA,RM4,THETA5,1,IERROR)
      IF (IERROR.GE.3) GO TO 121
C                 INCREASE THETA5
      THSV=THETA5
      IF (DTHETA.LT.TOL) GO TO 122
      DTHETA=DTHETA/2.
      THETA5=THETA5+DTHETA
      IERROR=-1
      GO TO 120
C                 DECREASE THETA5
121   IF (DTHETA.LT.TOL) GO TO 122
      DTHETA=DTHETA/2.
      THETA5=THETA5-DTHETA
      IERROR=-1
      GO TO 120
122   THETA5=THSV
      ISW=1
      GO TO 114
C     FIND LARGEST THETA5 FOR AXIS CASE
123   RMSQ=RM4*RM4
      THETA5=ASIN(SQRT((1.-1./RMSQ)/(GAMMA*(1+1./RMSQ))))
      THETA5=THETA5-.001
      ISW=1
      GO TO 114
124   CONTINUE
      GO TO 101
C
125   FORMAT (1H1,25X,7H*  *  *,//1X,57HTHIS PROGRAM PERFORMS A TYPE 3 S
     1HOCK INTERFERENCE PATTERN,//26X,7H*  *  */,11H RUN NUMBER,F7.2)
126   FORMAT (30H XL(SHOCK DISPLACEMENT LENGTH),F16.6,4H  FT)
127   FORMAT (12H NOSE RADIUS,20X,F15.5,4H  FT)
128   FORMAT (1X,6HOPTION,35X,A4)
129   FORMAT (1H1)
130   FORMAT (//1X,19HINPUT VARIABLES ARE/8H THETAI=,F9.4,4H DEG,5X,6HBE
     1TAI=,F9.4,4H DEG/)
131   FORMAT (//1X,10HRATIOS ARE/)
132   FORMAT (//7H REGION,5X,14HRELATIVE ANGLE,10X,14HABSOLUTE ANGLE,/9X
     1,5HTHETA,8X,4HBETA,7X,5HTHETA,8X,4HBETA,5X,13HUPSTREAM MACH,2X,10H
     2LOCAL MACH)
133   FORMAT (1X.I1,4F12.4,2F15.4)
```

```
134    FORMAT (//7H REGION,10X,1HP,12X,3HRHO,11X,1HT,11X,1HA,11X,1HU,13X,
      12HMU,3X,11HREYNOLDS NO,9H  MACH NO)
135    FORMAT (14X,3HPSI,4X,10HSLUG/CU FT,5X,7HRANKINE,6X,6HFT/SEC,6X,6HF
      1T/SEC,4X,11HSLUG/FT-SEC,11X,4H1/FT)
136    FORMAT (1X,I5,F12.4,F15.5,3F12.4,2E15.5,F8.4)
137    FORMAT (/1X,25HSTAGNATION CONDITIONS ARE/7H REGION,6X,5HPSTAG,12X,
      13HRHO,7X,5HTSTAG,4X,12HPSTAG/PSTAG1,/,14X,4HPSIA,4X,11HSLUGS/CU FT
      2,5X,7HRANKINE)
138    FORMAT (51H REGION 5 DOES NOT EXIST SINCE REGION 4 IS SUBSONIC)
139    FORMAT (/16X,45H *  *  *  *  *  *  *  *  *  *  *  *  *  *  **/)
140    FORMAT (//46H FOR A 3-DIMENSIONAL CASE THE FOLLOWING VALUES,28H RE
      1FER TO SURFACE CONDITIONS)
141    FORMAT (1X,7HBETA5 =,F10.3)
142    FORMAT (17H THETA5 RELATIVE=,F10.3,10H,ABSOLUTE=,F10.3/16H BETA5 R
      1ELATIVE=,F10.3,10H,ABSOLUTE=,F10.3)
143    FORMAT (7H P50P4=,F10.4,/)
144    FORMAT (1X,30HABSOLUTE VALUES AT CONDITION 5/1X,2HP=,F9.4,2X,4HRHO
      1=,E11.4,2X,2HT=,F9.4,2X,2HA=,F9.4,2X,2HU=,F9.4,2X,3HMU=,E11.4,2X
      2,12HREYNOLDS NO=,E11.4,2X,8HMACH NO=,F8.4)
145    FORMAT (14H   RHO WALL = ,E11.4/15H   VISC WALL = ,E11.4)
146    FORMAT (1H )
147    FORMAT (/23H PEAK PRESSURE RATIO   ,F8.4)
148    FORMAT (25H XI 13(SHEAR LAYER LENGTH),7X,F15.5,4H  FT)
149    FORMAT (48H STAG HEATING-3D NO INTERFERENCE (BTU/SQ FT-SEC),E15.5,
      120H  H(BTU/SQ-FT-SEC-R),E15.5,/)
150    FORMAT (//17X,26HSTANTON   Q(BTU/SQ FT-SEC),6X,9HDELTA(FT),6X,9HQR
      1ATIO-3D,6X,9HHRATIO-3D,)
151    FORMAT (1X,7HLAMINAR,2E18.5,3E15.5/10H TURBULENT,E16.5,E18.5,3E15.
      15)
       END
C      ...............................................................
```

Program Flow Chart – PRATC

Function PRATC computes the pressure ratio across a conical shock. The flow diagram is as follows:

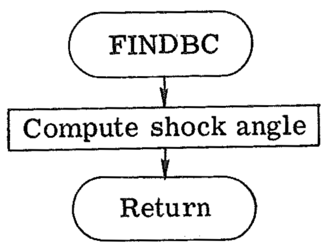


Program Listing – PRATC

```
      FUNCTION PRATC (RM,GAMMA,THETA)
C     CALCULATE PRESSURE RATIOS(P2S/P1) FOR AXISYMMETRICAL CASE ALONG
C     THE SHEAR LAYER
      RMSQ=RM*RM
      RM6=RM**6
      G2=1.-1./RMSQ
      G3=GAMMA*(1.+1./RMSQ)
      F1=(GAMMA+7.)/4.-(GAMMA-1.)**2/16.+6./RM6+(RMSQ-1.)/(RM**4*SIN(THE
     1TA))
      F2=.5*(GAMMA+7.)/(GAMMA+1.)*G2*(1.+1./RM6)
      F3=.5*(GAMMA+7.)/(GAMMA+1.)*G3*(1.+1./RM6)
      SINSQ=SIN(THETA)**2
      CP2S=.5*(F2+F1*SINSQ-SQRT((F2-F1*SINSQ)**2-((F3-F1)*SINSQ)**2))
C     PRESSURE ON SHEAR LAYER - P2S/P1
      PRATC=CP2S*RMSQ*GAMMA/2.+1.
      RETURN
      END
C     ................................................................
```

Program Flow Chart – FINDBC

Function FINDBC calculates the shock angle when a conical shock is assumed. The flow diagram is as follows:



Program Listing – FINDBC

```
      FUNCTION FINDBC (RM,GAMMA,THETA,IERROR)
C     CALCULATE BETA USING A CONICAL RELATIONSHIP
      PRINT=IERROR
      IERROR=0
      RMSQ=RM*RM
      G1=(GAMMA+1.)/2.
      G2=1.-1./RMSQ
      G3=GAMMA*(1.+1./RMSQ)
C     CHECK FOR STAND-OFF
      IF (THETA.GT.ASIN(SQRT(G2/G3))) GO TO 1
      SINSQ=SIN(THETA)**2
      C1=G2+G1*SINSQ
      C2=(G2-G1*SINSQ)**2
      C3=((G3-G1)*SINSQ)**2
      FINDBC=ASIN(SQRT(1./RM**2+.5*(C1-SQRT(C2-C3))))
      RETURN
1     IERROR=3
C     NO SOLUTION POSSIBLE
      THDEG=THETA*57.296
      IF (PRINT.GE.0) WRITE (6,2) RM,GAMMA,THDEG
      RETURN
C
2     FORMAT (38HNO SOLUTION FOUND FOR RM, GAMMA, THETA,3F10.4)
      END
C     ................................................................
```

USAGE

Program SHOCK for a type III interference pattern uses the standard FORTRAN NAMELIST input with $DATAIN as the NAMELIST name. The input includes the flow conditions, gas properties, impinging flow deflection or shock angle, shock displacement length, nose radius, and shear-layer angle relative to the local body slope. (See fig. 5.) The program can also increase the shock generator angle θ_i incrementally and the shear-layer angle $\bar{\theta}_5$ (if $\bar{\theta}_5$ is not specified) up to the maximum value for a type III interference. The ratio of shock displacement length to nose radius may also be used as an input instead of the individual lengths.

A description of the input and output variables and a sample case are presented.

Input Description

The $DATAIN input for type III is as follows:

RUN	run number for identification
RM1	M_∞, free-stream Mach number
GAMMA	c_p/c_v, ratio of specific heats
THETAI	θ_i, shock generator angle, deg; or β_i, impinging-shock angle, deg
TINCR	increment for θ_i (Default = 5°)
NTIMES	number of times to increment θ_i
IPT	initial point; 0 for stagnation conditions, 1 for free-stream static conditions
T	temperature at IPT, $^\circ$R
P	pressure at IPT, psia
AMW	molecular weight (used to compute gas constant)
TREF	reference temperature for computing viscosity, $^\circ$R
VREF	reference viscosity for computing viscosity, slugs/ft-sec

S	Sutherland's constant in viscosity equation
RB	nose radius, ft
TWALL	temperature at wall, ^{O}R
XL	L_{SH}, shock displacement length, ft
CP	c_p, specific heat at constant pressure, ft-lbf/slug-^{O}R
PR	N_{Pr}, Prandtl number
OPTION	AXIS for conical shock at shear-layer attachment; 2-D for plane shock at shear-layer attachment
TOL	acceptable tolerance for equal pressures (0.001)
ANGLE	THET if θ_i input; BETA if β_i input
XLRB	ratio of shock displacement length to nose radius (0 if XL and RB input)
THETA5	$\bar{\theta}_5$, shear-layer angle relative to local body slope, deg (optional, input as negative angle)
CKTH5	0 if $\bar{\theta}_5$ not input; 1 if $\bar{\theta}_5$ input

Output Description

The output from this program consists of printing only. A heading and pertinent input for identification are printed before the results of the calculations.

RUN NUMBER	run number for identification
M1	M_∞, Mach number in free stream
GAMMA(CP/CV)	ratio of specific heats
TEMP AT POINT "IPT"	input as T, ^{O}R
PRES AT POINT "IPT"	input as P, psia

MOLECULAR WEIGHT	molecular weight (used to compute gas constant)
REFERENCE TEMP	reference temperature for computing viscosity, ^{o}R
REFERENCE VISCOSITY	reference viscosity for computing viscosity, slugs/ft-sec
S(SUTHERLAND NUMBER)	Sutherland's constant in viscosity equation
TEMP AT WALL	T_w, ^{o}R
CP	c_p, specific heat at constant pressure, ft-lbf/slug-^{o}R
PRANDTL NUMBER	N_{Pr}, Prandtl number
XL(SHOCK DISPLACEMENT LENGTH)	length, ft
NOSE RADIUS	nose radius, ft
OPTION	type of calculation chosen (AXIS or 2-D)
THETAI	θ_i, shock generator angle, deg
BETAI	β_i, impinging shock angle, deg
P2/P1, etc.	p_2/p_1, etc., pressure ratios for regions listed
RHO2/1, etc.	ρ_2/ρ_1, etc., density ratios for regions listed
T2/T1, etc.	T_2/T_1, etc., temperature ratios for regions listed
A2/A1, etc.	a_2/a_1, etc., ratios of speeds of sound in regions listed
U2/U1, etc.	u_2/u_1, etc., velocity ratios for regions listed
RELATIVE ANGLE	
THETA	flow angle relative to flow in upstream region, deg
BETA	shock angle relative to flow in upstream region, deg

ABSOLUTE ANGLE

THETA	flow angle relative to free-stream flow, deg
BETA	shock angle relative to free-stream flow, deg
UPSTREAM MACH	Mach number in upstream region
LOCAL MACH	local Mach number
REGION	region in shock pattern
P	static pressure in region, psia
RHO	static density in region, slugs/ft^3
T	static temperature in region, ^{o}R
A	speed of sound in region, ft/sec
U	velocity in region, ft/sec
MU	static viscosity in region, slugs/ft-sec
REYNOLDS NO	Reynolds number per foot in region
MACH NO	Mach number in region

The following stagnation conditions are then listed:

PSTAG	total pressure in region, psia
RHO	total density in region, slugs/ft^3
TSTAG	total temperature in region, ^{o}R
PSTAG/PSTAG1	ratio of total pressure in region to free-stream total pressure

The pressure ratios and heat transfer for laminar and turbulent flow are listed as a function of conditions in region 5:

THETA5

RELATIVE	flow angle in region 5 relative to upstream flow, deg
ABSOLUTE	flow angle in region 5 relative to free-stream flow, deg

BETA5

RELATIVE	shock angle in region 5 relative to upstream flow, deg
ABSOLUTE	shock angle in region 5 relative to free-stream flow, deg
PEAK PRESSURE RATIO	ratio of peak pressure p_5 to stagnation pressure on sphere
XL13(SHEAR-LAYER LENGTH)	length of shear layer, ft
STAG HEATING 3D NO INTERFERENCE	stagnation-point heat-transfer rate on sphere, Btu/ft^2-sec
H	stagnation-point heat-transfer coefficient on sphere, Btu/ft^2-sec-$^{\circ}$R
STANTON	peak Stanton number
Q	peak heat-transfer rate, Btu/ft^2-sec
DELTA	shear-layer thickness at wall, ft
QRATIO-3D	Q_{pk}/Q_{stag}, ratio of peak heat-transfer rate to stagnation-point value
HRATIO-3D	H_{pk}/H_{stag}, ratio of peak heat-transfer coefficient to stagnation-point value

RHO WALL	density based on T_W
VISC WALL	viscosity based on T_W

Sample Case – Input

```
$DATAIN
RM1     =  0.6E+01,
GAMMA   =  0.14E+01,
THETAI  =  0.5E+01,
TINCR   =  0.5E+01,
NTIMES  =  1,
IPT     =  0,
T       =  0.9E+03,
P       =  0.4E+03,
AMW     =  0.2897E+02,
TREF    =  0.53E+03,
VREF    =  0.3801E-06,
RB      =  0.5E+00,
S       =  0.1986E+03,
TWALL   =  0.55E+03,
XL      =  0.2E+00,
CF      =  0.6006E+04,
PR      =  0.72E+00,
OPTION  =  0.14095221760901-267,
TOL     =  0.1E-02,
ANGLE   =  0.69404725765109E+93,
XLRB    =  0.0,
THETA5  =  0.2E+02,
CKTH5   =  0.1E+01,
RUN     =  0.1E+01,
$END
```

* * *

THIS PROGRAM PERFORMS A TYPE 3 SHOCK INTERFERENCE PATTERN

* * *

RUN NUMBER 1.00

INPUT VARIABLES ARE

M1	6.000	
GAMMA(CP/CV)	1.400000	
TEMP AT POINT 0	900.000000	RANKINE
PRES AT POINT 0	400.000000	PSI
MOLECULAR WEIGHT	28.970000	
REFERENCE TEMP	530.000000	RANKINE
REFERENCE VISCOSITY	3.801000E-07	SLUG/(FT-SEC)
S(SUTHERLAND NUMBER)	198.600	
TEMP AT WALL	550.000	RANKINE
CP	6006.000	FT-LBF/(SLUG-RANKINE)
PRANDTL NUMBER	.720000	
XL(SHOCK DISPLACEMENT LENGTH)	.200000	FT
NOSE RADIUS	.50000	FT
OPTION	AXIS	

INPUT VARIABLES ARE

THETAI= 5.0000 DEG BETAI= 13.1597 DEG

RATIOS ARE

P2/P1=	40.7108	RHO2/1=	5.2507	T2/T1=	7.7534	A2/A1=	2.7845	U2/U1=	.2491
P3/P1=	2.0103	RHO3/1=	1.6306	T3/T1=	1.2328	A3/A1=	1.1103	U3/U1=	.9837
P4/P3=	20.2512	RHO4/3=	4.6667	T4/T3=	4.3395	A4/A3=	2.0831	U4/U3=	.6396
P4/P1=	40.7104	RHO4/1=	7.6096	T4/T1=	5.3499	A4/A1=	2.3130	U4/U1=	.6292

REGION	RELATIVE ANGLE		ABSOLUTE ANGLE			
	THETA	BETA	THETA	BETA	UPSTREAM MACH	LOCAL MACH
2	-31.6177	99.4093	-31.6177	99.4093	6.0000	.5367
3	5.0000	13.1598	5.0000	13.1598	6.0000	5.3157
4	-36.6177	-51.9052	-31.6177	-46.9052	5.3157	1.6321

REGION	P	RHO	T	A	U	MU	REYNOLDS NO	MACH NO
	PSI	SLUG/CU FT	RANKINE	FT/SEC	FT/SEC	SLUG/FT-SEC	1/FT	
1	.2533	1.93645E-04	109.7561	513.5679	3081.4074	8.46377E-08	7.05004E+06	6.0000
2	10.3139	1.01677E-03	850.9825	1430.0257	767.4393	5.36831E-07	1.45355E+06	.5367
3	.5093	3.15760E-04	135.3111	570.2302	3031.1919	1.06990E-07	8.94597E+06	5.3157
4	10.3138	1.47356E-03	587.1804	1187.8711	1938.7491	4.10988E-07	6.95122E+06	1.6321

STAGNATION CONDITIONS ARE

REGION	PSTAG	RHO	TSTAG	PSTAG/PSTAG1
	PSIA	SLUGS/CU FT	RANKINE	
1	400.0000	3.72856E-02	900.0000	
2	12.5472	1.16958E-03	900.0000	.0314
3	386.5123	3.60280E-02	900.0088	.9663
4	45.9812	4.28605E-03	900.0088	.1150

```
               *  *  *  *  *  *  *  *  *  *  *  *  *  *  **

FOR A 3-DIMENSIONAL CASE THE FOLLOWING VALUES REFER TO SURFACE CONDITIONS
THETA5 RELATIVE=   -20.000,ABSOLUTE=   -51.617
BETA5 RELATIVE=   -46.119,ABSOLUTE=   -77.737
F5OP4=    1.6763

ABSOLUTE VALUES AT CONDITION 5
P=  17.2893  RHO= 2.1550E-03  T= 673.0642  A=1271.7794  U=1651.2774  MU= 4.5468E-07  REYNOLDS NO= 7.8263E+06  MACH NO=  1.2984
  RHO WALL =  2.6372E-03
  VISC WALL =  3.9108E-07


PEAK PRESSURE RATIO      1.4577
XL13(SHEAR LAYER LENGTH)                  .14221  FT
STAG HEATING-3D NO INTERFERENCE (BTU/SQ FT-SEC)    3.71457E+00  H(BTU/SQ-FT-SEC-R)    1.06130E-02


                STANTON    Q(BTU/SQ FT-SEC)      DELTA(FT)     QRATIO-3D     HRATIO-3D
LAMINAR        1.24518E-03      1.32119E+01     7.15164E-04   3.55679E+00   3.94415E+00
TURBULENT      1.48276E-03      1.62729E+01     1.75029E-02   4.38084E+00   4.69669E+00
```

PART IV – TYPE IV INTERFERENCE

PROBLEM DISCUSSION

Type IV interference can occur when the weak impinging shock intersects a strong bow shock ahead of a subsonic flow region, as shown in figure 1(d). In general, on a blunt body this shock intersection is located between the lower sonic point and just above the body axis, as shown in figure 2. The impinging shock causes a displacement of the bow shock and the formation of a supersonic jet that is embedded in the subsonic region. (See figs. 1(d) and 6.) A jet bow shock is produced when the jet impinges on the surface, creating a small region with high stagnation heating.

The flow model used in this discussion consists of a two-dimensional impinging shock intersecting the bow shock of a sphere in the vertical plane of symmetry. A sketch of the shock and jet pattern is shown in figure 7. The geometry of this complex flow pattern is calculated by using the following methods. The solution of the triple shock at point J_1 (flow conditions in regions 2, 3, and 4 and the shear-layer deflection angle) is obtained in the same manner discussed for type III in part III. As for type III, the free-stream flow conditions in region 1 and the angle θ_i or β_i are specified. The continuation of the bow shock between regions 3 and 5 and the shock between regions 4 and 6 are determined from the triple-point solution at point J_2. It is assumed that at point J_2 a shear layer (jet boundary) exists between regions 5 and 6 $(p_5 = p_6)$. The flow up through region 6 is supersonic with the exception that the flow in regions 2 and 5 is subsonic.

The location of point J_3 is determined from the shear-layer and shock angles surrounding region 4 and the shock displacement length L_{SH} $(J_1 - J_2)$, which must be obtained experimentally or by some approximate method. The pressure differential between regions 5 and 2 causes the jet to turn upward $(p_5 > p_2)$. Since the flow in region 7 must turn upward and the pressure p_7 must equal p_2 (shear layer between regions 7 and 2), a Prandtl-Meyer expansion fan centered at point J_3 occurs between regions 6 and 7. The line between J_3 and J_4 used to describe the jet geometry is constructed so that it bisects the expansion fan. Details of the intersection of the expansion fan with the reflected compression waves at point J_4 on the lower jet boundary are neglected because of the small distances and turning angles involved. Instead, a single compression wave centered at J_4 is used to turn the flow upward further and increase the pressure from region 7 to region 8. The pressure p_8 must equal p_5 since a shear layer exists between regions 8 and 5. Therefore, the conditions in regions 6 and 8 and all subsequent even-numbered regions in the jet are the same. Likewise, the conditions in all odd-numbered regions are the same. Also, the incremental increase in the flow deflection angle between adjacent regions is constant $\left(\text{i.e., } \theta_8 - \theta_7 = \theta_7 - \theta_6, \text{ etc.}\right)$. These approximations are justified since it was assumed that the mixing between the jet flow and the slowly moving flow in regions 2 and 5 is negligible. On the basis of this reasoning, an expansion fan centered at J_5 and intersecting the lower jet boundary at J_6 completes the jet geometry through region 8. (See ref. 7.) Peak heating at jet impingement is analogous to that on a blunt body submerged in a supersonic flow field of width $\overline{w}$. In order to calculate the heating, the location of the jet bow shock in the jet and the resulting jet stagnation velocity gradient at the wall must be determined. The location of the jet bow shock within the jet depends on the standoff distance of the complete shock configuration. Results obtained in reference 2 for $M_\infty = 6$ to 20 indicate that the nominal location of the jet bow shock is in either region 7 or region 8. Therefore, the jet stagnation heating is calculated by assuming that the jet bow shock lies near the center of either region 7 or region 8.

A flow model of the impingement of a supersonic jet on a plane surface is shown in figure 8. The flow conditions upstream of the jet bow shock are known from the previous analysis once the location of the jet bow shock is specified. The inclination of the jet α_j is assumed to be normal to the wall on the basis of measurements made in reference 2. The jet width $\overline{w}$ is the perpendicular distance from the jet boundary to the opposite junction for a specified region, as shown in figure 7. The jet bow shock is assumed to be a circular arc of radius R_c. At the wall the sonic line must be normal to the surface, and at the shock the jet-boundary streamline lies between the sonic line and the constant-pressure boundary, as shown in figure 8. It was shown in references 14 and 15 that this orientation of the sonic line is possible for $M_j < 2.8$ and $\gamma = 1.4$.

The velocity gradient along the wall in the jet stagnation region is calculated by using equation (6), where the Mach number and velocity are the values in the jet ahead of the bow shock for a specified region and the "jet body" radius R_{bj} is computed in the following manner: The data from references 1 and 2 indicate that the ratio of the standoff distance of the jet bow shock to the jet width $\delta_{js}/\overline{w}$ is approximately 0.45 for jet Mach numbers from 1.2 to 2.5 and $\gamma = 1.4$. The shock standoff distance is determined by multiplying the ratio by the calculated jet width for a specified region. The radius of the jet body, which in this case is assumed to be a sphere, is calculated by using the correlation shown in figure 17(a) of reference 16 for δ_{js}/R_{bj} as a function of the inverse of the normal-shock density ratio for a specified jet region and this value of δ_{js}. Therefore, the velocity gradient at the jet stagnation point is computed once the necessary quantities are known for the given region that includes the jet bow shock.

Another approach for calculating the velocity gradient at the jet stagnation point utilizes the Belotserkovskii strip integral method (refs. 17 and 18). It has been shown in reference 14 that this approach does not work for the low supersonic jet Mach numbers encountered in the present study $\left(M_j < 2.5\right)$. Therefore, empirical methods, such as the present relation between δ_{js} and $\overline{w}$, must be used to obtain the velocity gradient.

The heat transfer at the jet stagnation point for a given region (7 or 8) is calculated by using equation (5) of part III and the computed flow conditions and velocity gradient for that jet region. Equation (5) and the velocity-gradient equation (6) are also used to calculate the reference stagnation heating on a sphere by use of the physical body radius.

A simple expression for Q_{pk}/Q_{stag} derived in reference 1 is useful for predicting peak heating levels. This method is based on the same analogy as the present method but assumes a two-dimensional jet body at the impingement location. The expression from reference 1 is

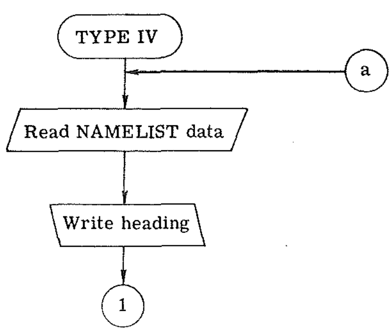
$$\frac{Q_{pk}}{Q_{stag}} = 1.03\left(\frac{R_b}{\overline{w}}\frac{p_{pk}}{p_{stag}}\right)^{0.5} \tag{7}$$

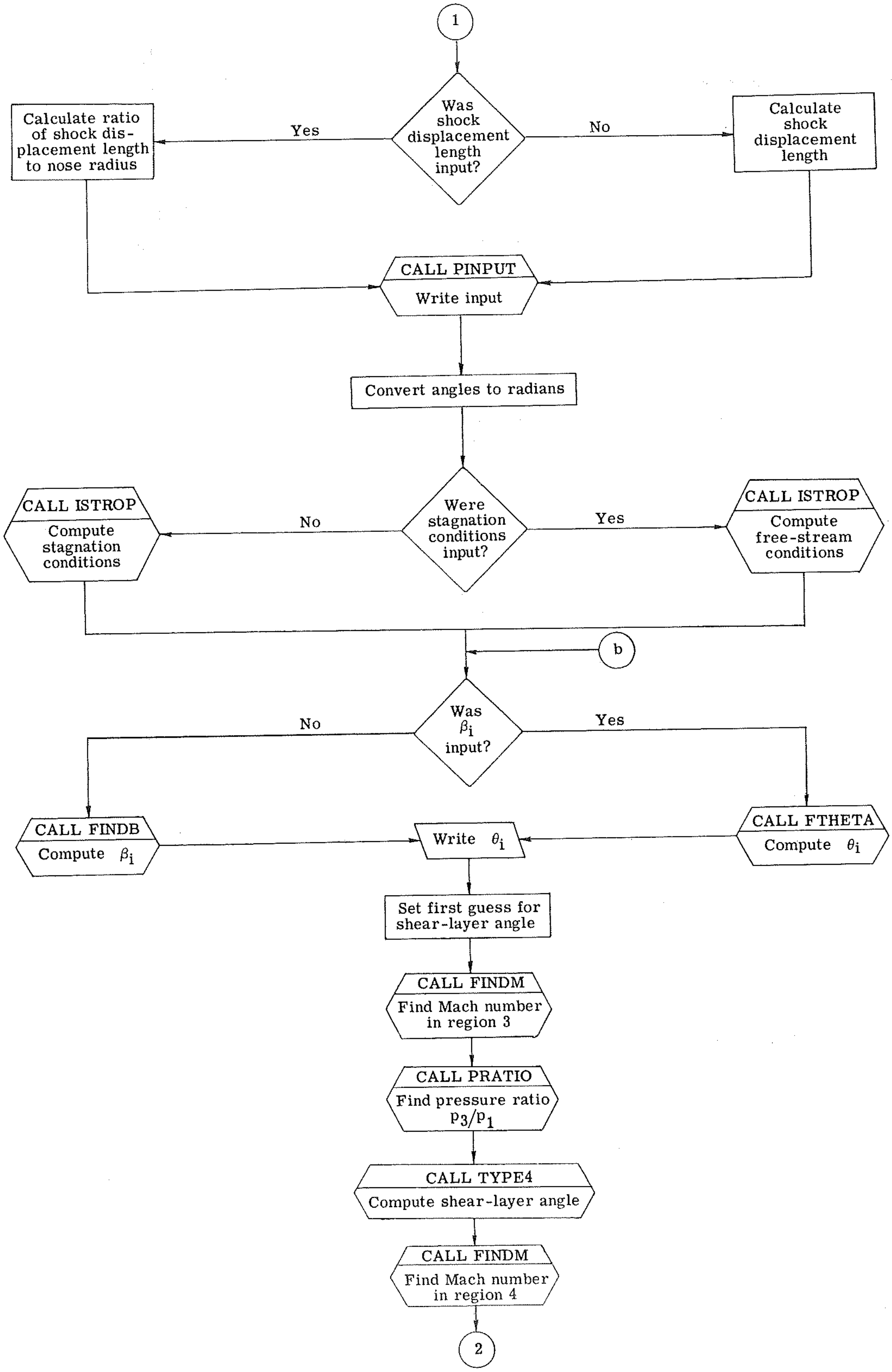
For the derivation of this expression, a wall to total temperature ratio of 0.5 and a Prandtl number of 0.7 were assumed.

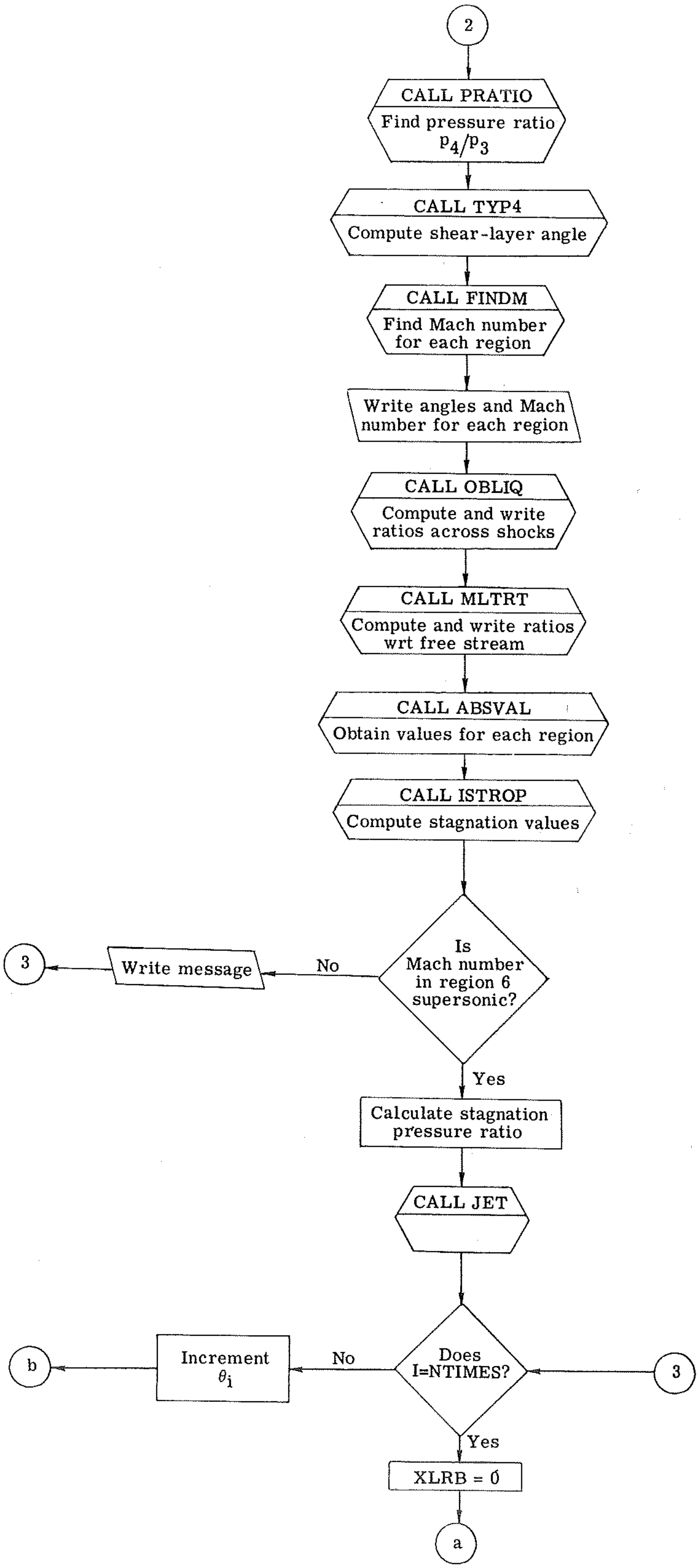
PROGRAM DESCRIPTION

The main program reads the input, calls the various subprograms, and computes the heat transfer. TYP4 calculates the flow deflection angle of the shear layer. FTHETA is called to compute the flow deflection angle, and FINDB is called to compute the shock angles in each region. The subprograms OBLIQ, FINDM, PRATIO, MLTRT, ABSVAL, and ISTROP compute flow variables and ratios of the flow variables. PINPUT prints the input variables. The flow charts and listings of these subprograms are presented in part VII. The main program for type IV interference calls JET to calculate the layout of the jet regions. JET calls HEAT to compute the jet stagnation and the reference heat-transfer values. The flow diagrams and listings for these two subprograms are presented after the main program listing. The flow diagram and listing for the main program follow.

Program Flow Chart – Main




1
Was shock displacement length input?
Yes
No
Calculate ratio of shock dis-placement length to nose radius
Calculate shock displacement length
CALL PINPUT
Write input
Convert angles to radians
Were stagnation conditions input?
No
Yes
CALL ISTROP
Compute stagnation conditions
CALL ISTROP
Compute free-stream conditions
b
Was β_i input?
No
Yes
CALL FINDB
Compute β_i
Write θ_i
CALL FTHETA
Compute θ_i
Set first guess for shear-layer angle
CALL FINDM
Find Mach number in region 3
CALL PRATIO
Find pressure ratio p_3/p_1
CALL TYPE4
Compute shear-layer angle
CALL FINDM
Find Mach number in region 4
2


2
CALL PRATIO
Find pressure ratio p_4/p_3
CALL TYP4
Compute shear-layer angle
CALL FINDM
Find Mach number for each region
Write angles and Mach number for each region
CALL OBLIQ
Compute and write ratios across shocks
CALL MLTRT
Compute and write ratios wrt free stream
CALL ABSVAL
Obtain values for each region
CALL ISTROP
Compute stagnation values
Is Mach number in region 6 supersonic?
No
Write message
3
Yes
Calculate stagnation pressure ratio
CALL JET
Does I=NTIMES?
3
No
Increment θ_i
b
Yes
XLRB = 0
a

Program Listing – Main

```
      PROGRAM SHOCK(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C     PURPOSE
C     THIS PROGRAM PERFORMS A TYPE 4 SHOCK INTERFERENCE PATTERN WITH
C     NORMAL IMPINGEMENT
C
      COMMON  PZ, RHOZ, TZ, P1OPZ, RHO1OZ, T1OTZ,
     1        PZ2, RHOZ2, TZ2, P2OPZ2, RHO2Z2, T2OTZ2,
     2        PZ3, RHOZ3, TZ3, P3OPZ3, RHO3Z3, T3OTZ3,
     3        PZ4, RHOZ4, TZ4, P4OPZ4, RHO4Z4, T4OTZ4,
     4        PZ5, RHOZ5, TZ5, P5OPZ5, RHO5Z5, T5OTZ5,
     5        PZ6, RHOZ6, TZ6, P6OPZ6, RHO6Z6, T6OTZ6,
     6        P2OP1, RHO2O1, T2OT1, A2OA1, U2OU1,
     7        P3OP1, RHO3O1, T3OT1, A3OA1, U3OU1,
     8        P4OP3, RHO4O3, T4OT3, A4OA3, U4OU3,
     9        P4OP1, RHO4O1, T4OT1, A4OA1, U4OU1,
     $        P5OP3, RHO5O3, T5OT3, A5OA3, U5OU3,
     $        P6OP4, RHO6O4, T6OT4, A6OA4, U6OU4,
     $        P5OP1, RHO5O1, T5OT1, A5OA1, U5OU1,
     $        P6OP1, RHO6O1, T6OT1, A6OA1, U6OU1
      COMMON  P1, RHO1, T1, A1, U1, VISC1, REY1,
     1        P2, RHO2, T2, A2, U2, VISC2, REY2,
     2        P3, RHO3, T3, A3, U3, VISC3, REY3,
     3        P4, RHO4, T4, A4, U4, VISC4, REY4,
     4        P5, RHO5, T5, A5, U5, VISC5, REY5,
     5        P6, RHO6, T6, A6, U6, VISC6, REY6
      DIMENSION VARI(17), VARD(17,1)
      DIMENSION RAT(30)
      EQUIVALENCE (RAT(1),P1)
      DIMENSION VALU1(7), VALUZ(7), RATIO(7), VALUJ(7)
      DIMENSION DELTA(2), CHWALL(2), TR(2), QRATE(2)
C     SET DEFAULTS FOR INPUT VARIABLES
      DATA GAMMA/1.4/,SVINC/5.0/,NTIMES/1/,IPT/0/,AMW/28.97/
      DATA THSVI/0./,BTSVI/0./
      DATA TREF/530.00/,VREF/.3801E-6/,RB/1.0/,S/198.6/,TWALL/530./
      DATA TOL/0.001/
      DATA XL/1.0/,CP/6006./,PR/.70/
      DATA BETA/4HBETA/
      DATA ANGLE/4HTHET/,TOL/.001/
      DATA RUN/1./
      DATA XLRB/0.0/
      NAMELIST /DATAIN/ RM1,GAMMA,THETAI,TINCR,NTIMES,IPT,T,P,AMW,TREF,V
     1REF,RB,S,TWALL,XL,CP,PR,TOL,IPRINT,XLRB,RUN,ANGLE
C     ..................................................................
C
C     INPUT DATA
C
C     ..................................................................
101   TINCR=SVINC
      THETAI=THSVI
      BETAI=BTSVI
      READ (5,DATAIN)
      IF (ENDFILE 5) 102,103
102   STOP
103   CONTINUE
      WRITE (6,DATAIN)
      WRITE (6,116) RUN
      THSVI=THETAI
      BTSVI=BETAI
```

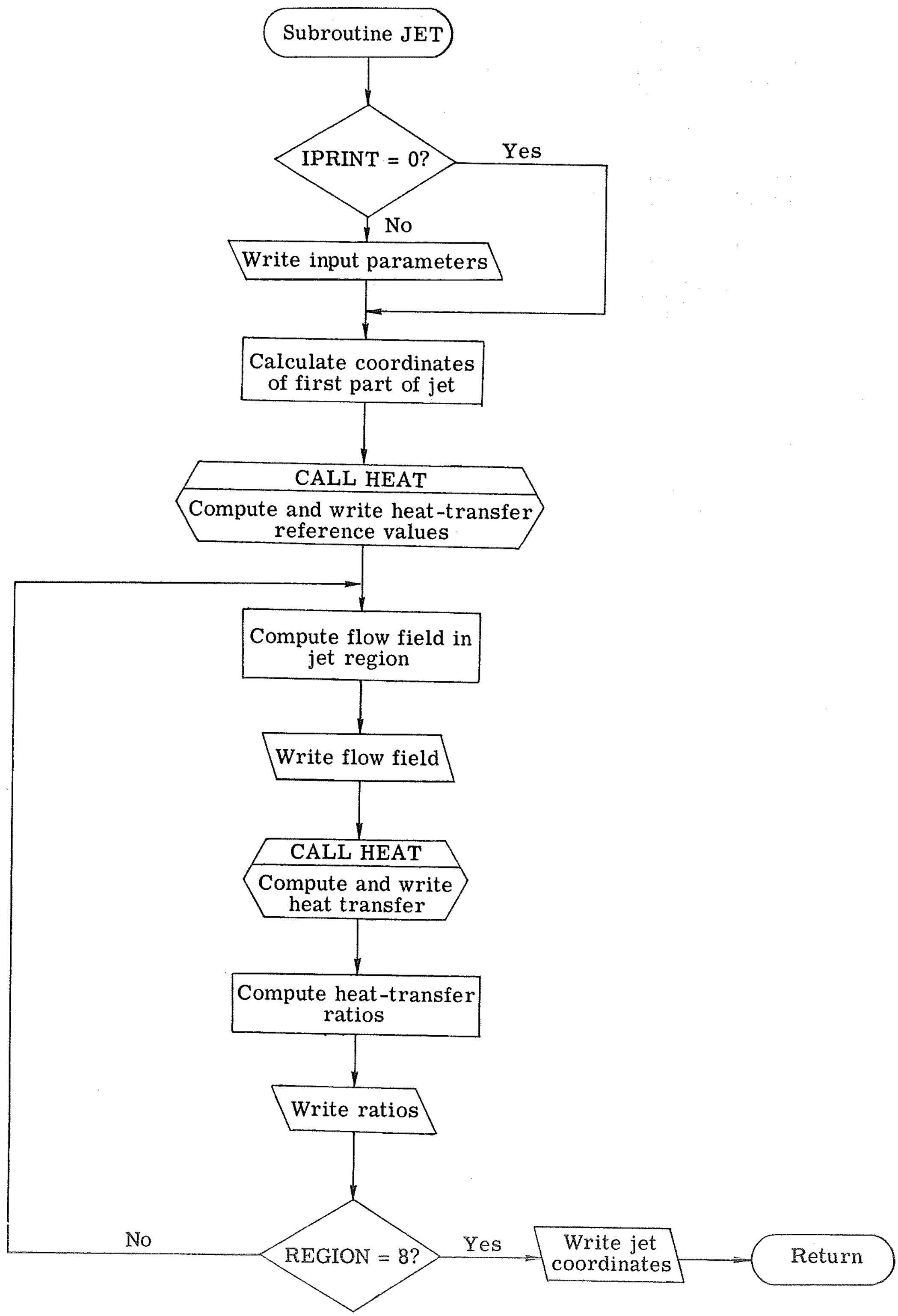
```
      SVINC=TINCR
      IF (XLRB.NE.0.0) GO TO 104
      XLRB=XL/RB
      GO TO 105
104   XL=XLRB*RB
105   CONTINUE
      XL12=XL
C     GAS CONSTANT(FT-LBF/LBM-R)
      R=1544.3/AMW
C     DENSITY  (SLUG/(CU FT)
      RHO=P*144./(32.2*R*T)
      CALL PINPUT (RM1,GAMMA,IPT,T,P,AMW,TREF,VREF,XL,S,TWALL,CP,PR)
      WRITE (6,117) XL12
      WRITE (6,118) RB
      THIDEG=THETAI
      THETAI=THETAI/57.296
      INPB=0
      TINCR=TINCR/57.296
      IF (IPT) 106,106,107
106   TZ=T
      RHOZ=RHO
      PZ=P
      GO TO 108
107   T1=T
      RHO1=RHO
      P1=P
108   CONTINUE
      CALL ISTROP (GAMMA,RM1,P1,PZ,P1OPZ,IPT)
      DO 115 I=1,NTIMES
      ISW=0
      IF (ANGLE.NE.BETA) GO TO 109
C     BETAI WAS INPUT INSTEAD OF THETAI
      BETAI=THETAI
      INPB=1
      THETAI=FTHETA(GAMMA,RM1,BETAI)
109   THIDEG=THETAI*57.296
      WRITE (6,119) THIDEG
C     .............................................................
C
C     CALCULATE AND WRITE PARAMETER RATIOS FOR 3/1
C
C     .............................................................
      BETAI=FINDB(GAMMA,RM1,THETAI,1,IERROR)
      IF (IERROR-2) 111,111,110
110   GO TO (101,101,101,101), IERROR
C                                ERRORS IN FINDING BETA
C                 IERROR = 1 ONE SOLUTION WAS FOUND, CONTINUE
C                          2 SOLUTION DID NOT CONVERGE, USE LAST B COMPUTED
C                          3 NO SOLUTION WAS FOUND, START NEW CASE
C                          4 NOT DEFINED
111   BIDEG=BETAI*180./3.1416
      THIDEG=THETAI*180./3.1416
C     .............................................................
C
C     ITERATE ON THETAF UNTIL P2 = P4
C
C     .............................................................
      THETAF=0.
      BETA2=1.5708
      RM3=FINDM(GAMMA,RM1,SIN(BETAI),BETAI,THETAI)
      P3OP1=PRATIO(GAMMA,RM1,SIN(BETAI))
C             A TYPE 4 INTERFERENCE PATTERN WITH INITIAL MACH NO RM1
```

```
C             ENTERING AT ANGLE 0 DEGREES
      CALL TYP4 (THETAF,BETA2,RM1,RM3,THETAI,THETA4,BETA4,P3OP1,GAMMA,TO
     1L,IERROR)
      IF (IERROR-3) 112,101,101
C     ..................................................................
C
C             A TYPE 4 INTERFERENCE PATTERN WITH INITIAL MACH NO M3
C             ENTERING AT ANGLE THETAI RADIANS
C
C     ..................................................................
112   BETA5=1.5708
      THETA5=0.
      RM4=FINDM(GAMMA,RM3,SIN(BETA4),BETA4,THETA4)
      P4OP3=PRATIO(GAMMA,RM3,SIN(BETA4))
      CALL TYP4 (THETA5,BETA5,RM3,RM4,THETA4,THETA6,BETA6,P4OP3,GAMMA,TO
     1L,IERROR)
      IF (IERROR-3) 113,101,101
C             WRITE THETA AND BETA ANGLES AND MACH NUMBER
113   WRITE (6,120)
      THFDEG=THETAF*57.296
      THFP=THETA5*57.296
      RM2=FINDM(GAMMA,RM1,SIN(BETA2),BETA2,ABS(THETAF))
      THETA2=THETAF
      THDEG=THETA2*180./3.1416
      IF (THETAF.LT.0) BETA2=3.1416-BETA2
      BETDEG=BETA2*180./3.1416
      ABSTH=THFDEG
      AAAT2=ABSTH
      ABSBT=BETDEG
      J=2
      WRITE (6,121) J,THDEG,BETDEG,ABSTH,ABSBT,RM1,RM2
      THDEG=THETAI*57.296
      BETDEG=BETAI*57.296
      ABSTH=THIDEG
      ABSBT=BIDEG
      J=3
      WRITE (6,121) J,THDEG,BETDEG,ABSTH,ABSBT,RM1,RM3
      THDEG=THETA4*180./3.1416
      BETDEG=BETA4*180./3.1416
      ABSTH=THFDEG
      ABSBT=THIDEG-BETDEG
      AAAB4=ABSBT
      J=4
      WRITE (6,121) J,THDEG,BETDEG,ABSTH,ABSBT,RM3,RM4
      RM5=FINDM(GAMMA,RM3,SIN(BETA5),BETA5,ABS(THETA5))
      THDEG=THETA5*57.296
      IF (THETA5.LT.0) BETA5=3.1416-BETA5
      BETDEG=BETA5*57.296
      ABSTH=THIDEG-THFP
      ABSBT=THIDEG-BETDEG
      J=5
      WRITE (6,121) J,THDEG,BETDEG,ABSTH,ABSBT,RM3,RM5
      RM6=FINDM(GAMMA,RM4,SIN(BETA6),BETA6,THETA6)
      THDEG=THETA6*57.296
      BETDEG=BETA6*57.296
      ABSTH=THIDEG-THFP
      AAAT6=ABSTH
      ABSBT=THFDEG+BETDEG
      ABB6=ABSBT
      J=6
      WRITE (6,121) J,THDEG,BETDEG,ABSTH,ABSBT,RM4,RM6
C     ..................................................................
```

```
C
C     CALCULATE AND WRITE PARAMETER RATIOS FOR 2/1, 4/3, 4/1
C
C     .......................................................................
      IO=2
      WRITE (6,122)
      CALL OBLIQ (GAMMA,RM1,ABS(THETAF),BETA2,RM2,P2OP1,1,2,IO)
      CALL OBLIQ (GAMMA,RM1,THETAI,BETAI,RM3,P3OP1,1,3,IO)
      CALL OBLIQ (GAMMA,RM3,THETA4,BETA4,RM4,P4OP3,3,4,IO)
      CALL OBLIQ (GAMMA,RM3,ABS(THETA5),BETA5,RM5,P5OP3,3,5,IO)
      CALL OBLIQ (GAMMA,RM4,THETA6,BETA6,RM6,P6OP4,4,6,IO)
      CALL MLTRT (P4OP3,P3OP1,P4OP1,1,4,1)
      CALL MLTRT (P5OP3,P3OP1,P5OP1,1,5,1)
      CALL MLTRT (P6OP4,P4OP1,P6OP1,1,6,1)
C     .......................................................................
C
C     CALCULATE ABSOLUTE VALUES FOR POINTS 0 THRU 4
C
C     .......................................................................
      WRITE (6,123)
      WRITE (6,124)
      VISC1=VISCJ(VREF,TREF,T1,S)
      A1=SQRT(32.2*GAMMA*R*T1)
      U1=A1*RM1
      REY1=RHO1*U1/VISC1
      J=1
      WRITE (6,125) J,P1,RHO1,T1,A1,U1,VISC1,REY1,RM1
      IO=1
      J=2
      CALL ABSVAL (P2OP1,P1,P2,VREF,TREF,S,J,IO,RM2)
      J=3
      CALL ABSVAL (P3OP1,P1,P3,VREF,TREF,S,J,IO,RM3)
      J=4
      CALL ABSVAL (P4OP1,P1,P4,VREF,TREF,S,J,IO,RM4)
      J=5
      CALL ABSVAL (P5OP1,P1,P5,VREF,TREF,S,J,IO,RM5)
      J=6
      CALL ABSVAL (P6OP1,P1,P6,VREF,TREF,S,J,IO,RM6)
      WRITE (6,126)
      J=1
      WRITE (6,125) J,PZ,RHOZ,TZ
      J=2
      CALL ISTROP (GAMMA,RM2,P2,PZ2,P2OPZ2,2)
      PZ2OZ=PZ2/PZ
      WRITE (6,125) J,PZ2,RHOZ2,TZ2,PZ2OZ
      J=3
      CALL ISTROP (GAMMA,RM3,P3,PZ3,P3OPZ3,3)
      PZ3OZ=PZ3/PZ
      WRITE (6,125) J,PZ3,RHOZ3,TZ3,PZ3OZ
      J=4
      CALL ISTROP (GAMMA,RM4,P4,PZ4,P4OPZ4,4)
      PZ4OZ=PZ4/PZ
      WRITE (6,125) J,PZ4,RHOZ4,TZ4,PZ4OZ
      J=5
      CALL ISTROP (GAMMA,RM5,P5,PZ5,P5OPZ5,5)
      PZ5OZ=PZ5/PZ
      WRITE (6,125) J,PZ5,RHOZ5,TZ5,PZ5OZ
      J=6
      CALL ISTROP (GAMMA,RM6,P6,PZ6,P6OPZ6,6)
      PZ6OZ=PZ6/PZ
      WRITE (6,125) J,PZ6,RHOZ6,TZ6,PZ6OZ
      IF (RM6.GE.1.) GO TO 114
```

```
      WRITE (6,127)                                                      A 246
      GO TO 115                                                          A 247
C                 CALCULATE AMPLIFICATION FACTOR                         A 248
114
      CALL JET (GAMMA,AAAB4,AAAT2,P2,PZ6,RM6,AAAT6,CP,TZ6,PR,VREF,TWALL,  A 252
     1TREF,AMW,S,PZ2,RM1,T1,PZ,ABB6,XLRB,RB,IPRINT)                      A 253
115   THETAI=THETAI+TINCR                                                A 254
      XLRB=0.                                                            A 255
      GO TO 101                                                          A 256
C                                                                        A 257
116   FORMAT (1H1,25X,9H*  *  * ,//1X,81HTHIS PROGRAM PERFORMS A TYPE 4  A 258
     1SHOCK INTERFERENCE PATTERN WITH NORMAL IMPINGEMENT,//26X,7H*  *  * A 259
     2/,11H RUN NUMBER,F7.2)                                             A 260
117   FORMAT (30H XL(SHOCK DISPLACEMENT LENGTH),F16.6,4H  FT)            A 261
118   FORMAT (12H NOSE RADIUS,18X,F15.5,4H  FT)                          A 262
119   FORMAT (1H1,19HTHETAI        =      ,F8.4,6H   DEG)                A 263
120   FORMAT (//12X,14HRELATIVE ANGLE,10X,14HABSOLUTE ANGLE,/9X,5HTHETA, A 264
     18X,4HBETA,7X,5HTHETA,8X,4HBETA,5X,13HUPSTREAM MACH,2X,10HLOCAL MAC A 265
     2H)                                                                 A 266
121   FORMAT (1X,I1,4F12.4,5X,F12.4,5X,F12.4)                            A 267
122   FORMAT (//1X,10HRATIOS ARE/)                                       A 268
123   FORMAT (//7H REGION,11X,1HP,12X,3HRHO,11X,1HT,11X,1HA,11X,1HU,13X, A 269
     12HMU,3X,11HREYNOLDS NO,9H  MACH NO)                                A 270
124   FORMAT (15X,3HPSI,4X,11HSLUGS/CU FT,5X,7HRANKINE,6X,6HFT/SEC,6X,6H A 271
     1FT/SEC,4X,11HSLUG/FT-SEC,11X,4H1/FT)                               A 272
125   FORMAT (1X,I5,F12.4,E15.5,3F12.4,2E15.5,F8.4)                      A 273
126   FORMAT (/1X,25HSTAGNATION CONDITIONS ARE/7H REGION,6X,5HPSTAG,12X, A 274
     13HRHO,7X,5HTSTAG,4X,12HPSTAG/PSTAG1,/,14X,4HPSIA,4X,11HSLUGS/CU FT A 275
     2,5X,7HRANKINE)                                                     A 276
127   FORMAT (1H0,57HMACH NO. IN REGION 6 IS LESS THAN 1.0 ... GO TO NEX A 277
     1T CASE)                                                            A 278
      END                                                                A 279-
```

Program Flow Chart – JET

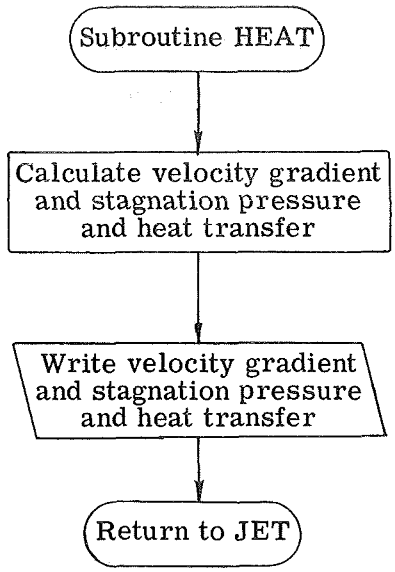


```
      SUBROUTINE JET (GAMMA,B4,THET2,P2,P06,AM6,THET6,CP,T06,PR,AMUR,TW,
     1TR,AMWT,S,P02,AM1,T1,P01,B6,XLRB,RB,IPRINT)
      DIMENSION XJ(15), YJ(15), THET(15)
      DIMENSION VARI(11), VARD(11,1)
      DATA VARI/.12,.24,.34,.42,.495,.56,.605,.65,.69,.725,.76/
      DATA VARD/.1,.2,.3,.4,.5,.6,.7,.8,.9,1.,1.1/
1     IF (IPRINT.EQ.0) GO TO 2
      WRITE (6,10) GAMMA,B4,THET2,P2,P06,AM6,CP,T06,PR,AMUR,TW,TR,AMWT,S
     1,THET6,P02,AM1,T1,B6
2     KODE=1
      PI=3.1415927
      RTD=180.0/PI
      THET(2)=THET2/RTD
      THET(6)=THET6/RTD
      B4R=B4/RTD
      B6R=B6/RTD
      XL12=XLRB*RB
      XL13=XL12*(SIN(B4R)-COS(B4R)*TAN(B6R))/(SIN(THET(2))-COS(THET(2))*
     1TAN(B6R))
      XJ(1)=0.
      YJ(1)=0.
      XJ(2)=XL12*COS(B4R)
      YJ(2)=XL12*SIN(B4R)
      XJ(3)=XL13*COS(THET(2))
      YJ(3)=XL13*SIN(THET(2))
      GP1=GAMMA+1.
      GM1=GAMMA-1.
      GPOM=GP1/GM1
      GMOP=GM1/GP1
      P7=P2
      P07=P06
      PR7=P7/P07
      Z1=PR7**(-GM1/GAMMA)-1.
      IF (Z1.GE.0.) GO TO 3
      WRITE (6,11) Z1
      CALL EXIT
3     CONTINUE
      AM7=SQRT(2./GM1*Z1)
      AMUB6R=ASIN(1./AM6)
      AMUB6D=RTD*AMUB6R
      AMUB7R=ASIN(1./AM7)
      AMUB7D=RTD*AMUB7R
      IF (AM6.GE.1.0) GO TO 4
      WRITE (6,12) AM6
      CALL EXIT
4     IF (AM7.GE.1.0) GO TO 5
      WRITE (6,13) AM7
      CALL EXIT
5     Z2=SQRT(GMOP*(AM6**2-1.))
      Z3=SQRT(AM6**2-1.)
      ANU6R=SQRT(GPOM)*ATAN(Z2)-ATAN(Z3)
      ANU6D=ANU6R*RTD
      Z4=SQRT(GMOP*(AM7**2-1.))
      Z5=SQRT(AM7**2-1.)
      ANU7R=SQRT(GPOM)*ATAN(Z4)-ATAN(Z5)
      ANU7D=ANU7R*RTD
      DTHET=ANU7R-ANU6R
      DELTA=(AMUB6R+AMUB7R+DTHET)*0.5
      EPS=DELTA-DTHET-THET(6)
```

```
      AN7=EPS
      DTHETD=RTD*DTHET
      DELTAD=RTD*DELTA
      EPSD=RTD*EPS
      AN7D=RTD*AN7
      XJ(4)=(YJ(3)-YJ(2)+XJ(2)*TAN(THET(6))+XJ(3)*TAN(AN7))/(TAN(AN7)+TA
     1N(THET(6)))
      YJ(4)=YJ(2)+(XJ(4)-XJ(2))*TAN(THET(6))
      ZLJ=SQRT((XJ(4)-XJ(3))**2+(YJ(4)-YJ(3))**2)
      ZLK=2.*ZLJ*COS(DELTA)
      EPS8=DELTA-DTHET
      ZLM=2.*ZLJ*COS(EPS8)
      ZW8=ZLJ*SIN(EPS8)
      ZW7=ZLJ*SIN(DELTA)
      TTS=SQRT(2.*CP*TO6)
C     CONSTANT  INPUT  TO  SUBROUTINE  HEAT
C
      RG=1545./AMWT
      AQ=(0.76/PR**(.6))/(778.26*SQRT(32.2))
      AMUW=VISCJ(AMUR,TR,TW,S)
      AMU1=VISCJ(AMUR,TR,TO6,S)
      DQ=CP*(TO6-TW)
      AM12=AM1**2
C
C     CALCULATION  OF  UGRDTS
C
      U1=AM1*SQRT(GAMMA*RG*T1*32.2)
      WRITE (6,14)
      CALL HEAT (RG,TW,TO6,AMUW,AMU1,AQ,DQ,UGRDTS,PSNI,PO1,AM12,GP1,GM1,
     1GAMMA,QWS,U1,RB)
C
C     BEGIN LOOPING
C
      MAXR=2
      NREG=6
      DO 9 I=1,MAXR
      NREG=NREG+1
      NREGM1=NREG-1
      NREGM2=NREG-2
      NREGM4=NREG-4
      THET(NREG)=THET(NREGM1)+DTHET
      THETD=THET(NREG)*RTD
      ALPHA=90.
      ALPI=ALPHA+THET(NREG)*RTD
      ALPHAP=ALPHA
      SIGN=1.
      IF (ALPHA.LE.90.) GO TO 6
      ALPHA=180.-ALPHA
      SIGN=-1.
 6    CONTINUE
      IF (MOD(NREG,2).EQ.0) GO TO 7
      XJ(NREGM2)=XJ(NREGM4)+ZLK*COS(THET(NREG))
      YJ(NREGM2)=YJ(NREGM4)+ZLK*SIN(THET(NREG))
      ZLW=ZW7
      RMACH=AM7
      GO TO 8
 7    ZLW=ZW8
      RMACH=AM6
      XJ(NREGM2)=XJ(NREGM4)+ZLM*COS(THET(NREG))
      YJ(NREGM2)=YJ(NREGM4)+ZLM*SIN(THET(NREG))
 8    WRITE (6,15) NREG
      T7=TO6/(1.+GM1/2.*RMACH**2)
```

```
      U7=RMACH*SQRT(GAMMA*RG*T7*32.2)
      DELOW=.45
      SDS=DELOW*ZLW
      SMACH=RMACH**2
      ABC=2.+GM1*SMACH
      RHOJOS=ABC/(GP1*SMACH)
      CALL MTLUP (RHOJOS,DELOR,1,11,11,1,-1,VARI,VARD)
      RN=SDS/DELOR
      WRITE (6,16) THETD,ZLW,RMACH,RN
      CALL HEAT (RG,TW,T06,AMUW,AMU1,AQ,DQ,UGRDT,PW,P06,SMACH,GP1,GM1,GA
     1MMA,QW,U7,RN)
      RQW=QW/QWS
      RL=RB/ZLW
      PWRI=PW/PSNI
      RTLR=RB/XL13
      RLJ=XL13/ZLW
      RATLJ=RLJ*PWRI
      PWR=PSNI/PW
      QRED=1.03*SQRT(RL/PWR)
      WRITE (6,17) RL,PWRI,RQW,QRED
    9 CONTINUE
      WRITE (6,18) (XJ(I),YJ(I),I=1,6)
      RETURN
C
   10 FORMAT (1H0,8HGAMMA = ,E12.5,9X,5HB4 = ,E12.5,13X,8HTHET2 = ,E12.5
     1,10X,5HP2 = ,E12.5,/,1H ,6HP06 = ,E12.5,11X,6HAM6 = ,E12.5,12X,5HC
     2P = ,E12.5,13X,6HT06 = ,E12.5,/,1H ,5HPR = ,E12.5,12X,7HAMUR = ,E1
     32.5,11X,5HTW = ,E12.5,13X,5HTR = ,E12.5,/,1H ,7HAMWT = ,E12.5,10X,
     44HS = ,E12.5,14X,8HTHET6 = ,E12.5,10X,6HP02 = ,E12.5,/,1H ,6HAM1 =
     5 ,E12.5,11X,5HT1 = ,E12.5,13X,5HB6 = ,E12.5,//)
   11 FORMAT (1H0,23HERROR MESSAGE ... Z1 = ,E12.5,//)
   12 FORMAT (1H0,24HERROR MESSAGE ... AM6 = ,E12.5,//)
   13 FORMAT (1H0,24HERROR MESSAGE ... AM7 = ,E12.5,//)
   14 FORMAT (1H0,41HCONDITIONS WITHOUT SHOCK INTERFERENCE ARE)
   15 FORMAT (//,1H0,21HCONDITIONS IN REGION ,I2)
   16 FORMAT (1H0,8HTHETA = ,E12.5,4H DEG,3X,12HJET WIDTH = ,E12.5,5H FE
     1ET,3X,11HMACH NO. = ,E12.5,3X,15H NOSE RADIUS = ,E12.5,5H FEET)
   17 FORMAT (1H ,30HRATIO NOSE RADIUS TO JET WIDTH,24X,3H = ,E12.5,/,1H
     1 ,26HP WALL/P PITOT FREE STREAM,28X,3H = ,E12.5,/,1H ,57HHEAT TRAN
     2SFER RATIO (WITH INTERFERENCE TO 3-D WITHOUT) = ,E12.5,/,1H ,26HHE
     3AT TRANSFER RATIO(EDNEY),27X,3H = ,E12.5)
   18 FORMAT (//27H COORDINATES OF THE JET ARE,/,1H0,4HJ1 (,E12.5,1H,,E1
     12.5,1H),/,1H ,4HJ2 (,E12.5,1H,,E12.5,1H),/,1H ,4HJ3 (,E12.5,1H,,E1
     22.5,1H),/,1H ,4HJ4 (,E12.5,1H,,E12.5,1H),/,1H ,4HJ5 (,E12.5,1H,,E1
     32.5,1H),/,1H ,4HJ6 (,E12.5,1H,,E12.5,1H))
      END
```

Program Flow Chart – HEAT



Program Listing – HEAT

```
C     ..................................................................
      SUBROUTINE HEAT (RG,TW,T06,AMUW,AMU1,AQ,DQ,UGRDT,PW,P01,AM12,GP1,G
     1M1,GAMMA,QW,U,R)
      TERM1=(GP1*AM12)/(GM1*AM12+2.)
      TERM2=GP1/(2.*GAMMA*AM12-GM1)
      PW=P01*TERM1**(GAMMA/GM1)*TERM2**(1./GM1)
      UGRDT=U/R*SQRT(GM1/GAMMA*(1.+2./(GM1*AM12))*(1.-1./(GAMMA*AM12)))
      BQ=((144.*AMUW)/(RG*TW))**(.1)
      CQ=((144.*AMU1)/(RG*T06))**(.4)
      EQ1=PW**.5
      QW=AQ*BQ*CQ*DQ*EQ1*SQRT(UGRDT)
      WRITE (6,1) PW,UGRDT,QW
      RETURN
C
1     FORMAT (1H0,22HWALL PRESSURE        = ,E12.5,4H PSI,/1H ,22HVELOCIT
     1Y GRADIENT    = ,E12.5,6H 1/SEC,/,1H ,22HSTAGNATION HEATING   = ,E12
     2.5,14H BTU/SQ.FT-SEC,/)
      END
```

USAGE

Program SHOCK for a type IV interference pattern uses the standard FORTRAN NAMELIST input with $DATAIN as the NAMELIST name. The input includes the flow conditions, gas properties, flow deflection or shock angle, shock displacement length L_{SH} (see fig. 6), and nose radius. The program can increment the shock generator angle and lists the peak pressure and heat transfer in regions 7 and 8 (see fig. 7) for each angle.

A description of the input and output variables and a sample case are presented.

Input Description

The $DATAIN input for type IV is as follows:

RUN	run number for identification
RM1	M_∞, free-stream Mach number
GAMMA	c_p/c_v, ratio of specific heats
THETAI	θ_i, shock generator angle, deg; or β_i, impinging shock angle, deg
TINCR	increment for θ_i (Default = 5^o)
NTIMES	number of times to increment θ_i
IPT	initial point; 0 for stagnation conditions, 1 for free-stream static conditions
T	temperature at IPT, ^oR
P	pressure at IPT, psia
AMW	molecular weight (used to compute gas constant)
TREF	reference temperature for computing viscosity, ^oR
VREF	reference viscosity for computing viscosity, slugs/ft-sec
RB	nose radius, ft
S	Sutherland's constant in viscosity equation
TWALL	temperature at wall, ^oR
XL	L_{SH}, shock displacement length $(J_1 - J_2$ in fig. 7), ft
XLRB	ratio of shock displacement length to nose radius (may be input in place of XL)

CP	c_p, specific heat at constant pressure, ft-lbf/slug-$^{\circ}$R
PR	N_{Pr}, Prandtl number
TOL	acceptable tolerance for equal pressures (0.001)
ANGLE	THET if θ_i input; BETA if β_i input
IPRINT	0 to suppress extra printout; 1 for complete printout

Output Description

RUN NUMBER	run number for identification
M1	M_∞, Mach number in free stream
GAMMA (CP/CV)	ratio of specific heats
TEMP AT POINT "IPT"	input as T, $^{\circ}$R
PRES AT POINT "IPT"	input as P, psia
MOLECULAR WEIGHT	molecular weight (used to compute gas constant)
REFERENCE TEMP	reference temperature for computing viscosity, $^{\circ}$R
REFERENCE VISCOSITY	reference viscosity for computing viscosity, slugs/ft-sec
S(SUTHERLAND NUMBER)	Sutherland's constant in viscosity equation
TEMP AT WALL	T_w, $^{\circ}$R
CP	c_p, specific heat at constant pressure, ft-lbf/slug-$^{\circ}$R
PRANDTL NUMBER	N_{Pr}, Prandtl number
XL(SHOCK DISPLACEMENT LENGTH)	distance from J_1 to J_2 (see fig. 7), ft

NOSE RADIUS	nose radius, ft
THETAI	θ_i, shock generator angle, deg
RELATIVE ANGLE	
THETA	flow angle relative to flow in upstream region, deg
BETA	shock angle relative to flow in upstream region, deg
ABSOLUTE ANGLE	
THETA	flow angle relative to free-stream flow, deg
BETA	shock angle relative to free-stream flow, deg
UPSTREAM MACH	Mach number in upstream region
LOCAL MACH	local Mach number
P2/P1, etc.	p_2/p_1, etc., pressure ratios for regions listed
RHO2/1, etc.	ρ_2/ρ_1, etc., density ratios for regions listed
T2/T1, etc.	T_2/T_1, etc., temperature ratios for regions listed
A2/A1, etc.	a_2/a_1, etc., ratios of speeds of sound in regions listed
U2/U1, etc.	u_2/u_1, etc., velocity ratios for regions listed
REGION	region in shock pattern
P	static pressure for region, psia
RHO	static density for region, slugs/ft^3
T	static temperature for region, $^{\circ}$R
A	speed of sound for region, ft/sec

U	velocity for region, ft/sec
MU	static viscosity in region, slugs/ft-sec
REYNOLDS NO	Reynolds number per foot in region
MACH NO	Mach number in region

The following stagnation conditions are then listed:

PSTAG	total pressure in region, psia
RHO	total density in region, $slugs/ft^3$
TSTAG	total temperature in region, ^oR
PSTAG/PSTAG1	ratio of total pressure in region to free-stream total pressure

Reference conditions without interference are listed as

WALL PRESSURE	p_{stag}, stagnation pressure on sphere, psia
VELOCITY GRADIENT	stagnation velocity gradient on sphere, 1/sec
STAGNATION HEATING	Q_{stag}, stagnation-point heat-transfer rate on sphere, Btu/ft^2-sec

The peak conditions for regions 7 and 8 are listed as follows:

THETA	jet flow angle, deg
JET WIDTH	$\overline{w}$, jet width, ft
MACH NO.	jet Mach number
NOSE RADIUS	R_{bj}, nose radius of "jet body," ft
WALL PRESSURE	peak pressure at wall (jet stagnation pressure), psia

VELOCITY GRADIENT $\left(\frac{du_w}{ds}\right)_{stag}$, jet stagnation velocity gradient, 1/sec

STAGNATION HEATING Q_{pk}, jet stagnation heat-transfer rate, Btu/ft^2-sec

RATIO NOSE RADIUS TO JET WIDTH $R_b/\overline{w}$

PWALL/P PITOT FREE STREAM p_{pk}/p_{stag}

HEAT TRANSFER RATIO Q_{pk}/Q_{stag}, ratio of peak heating in region to reference heating on sphere

HEAT TRANSFER RATIO (EDNEY) Q_{pk}/Q_{stag}, heating ratio calculated from equation (7)

COORDINATES OF JET (J1 to J6) coordinates of jet as defined in figure 7

Sample Case – Input

```
$DATAIN
RM1      =  0.6E+01,
GAMMA    =  0.14E+01,
THETAI   =  0.5E+01,
TINCR    =  0.5E+01,
NTIMES   =  1,
IPT      =  0,
T        =  0.9E+03,
P        =  0.4E+03,
AMW      =  0.2897E+02,
TREF     =  0.53E+C3,
VREF     =  0.3801E-C6,
RB       =  0.5E+0C,
S        =  0.1986E+03,
TWALL    =  0.55E+C3,
XL       =  0.15E+CC,
```

```
CP       =   0.6CC6E+04,
PR       =   0.72E+00,
TOL      =   0.1E-02,
IPRINT   =   0,
XLRB     =   0.0,
RUN      =   0.1E+01,
ANGLE    =   0.69404725765109E+93,
$END
```

Sample Case – Output

```
THIS PROGRAM PERFORMS A TYPE 4 SHOCK INTERFERENCE PATTERN WITH NORMAL IMPINGEMENT

                              *   *   *
RUN NUMBER   1.00

INPUT VARIABLES ARE

MI                                        6.000
GAMMA(CP/CV)                           1.400000
TEMP AT POINT 0                      900.000000   RANKINE
PRES AT POINT 0                      400.000000   PSI
MOLECULAR WEIGHT                      28.970000
REFERENCE TEMP                       53C.000000   RANKINE
REFERENCE VISCOSITY                3.801000E-07   SLUG/(FT-SEC)
S(SUTHERLAND NUMBER)                    198.600
TEMP AT WALL                            550.000   RANKINE
CP                                     6006.C00   FT-LBF/(SLUG-RANKINE)
PRANDTL NUMBER                          .720000
XL(SHOCK DISPLACEMENT LENGTH)           .150000   FT
NOSE RADIUS                             .50000  FT
```

THETAI = 5.0000 DEG

	RELATIVE ANGLE THETA	RELATIVE ANGLE BETA	ABSOLUTE ANGLE THETA	ABSOLUTE ANGLE BETA	UPSTREAM MACH	LOCAL MACH
2	-31.6175	99.4092	-31.6177	99.4092	6.0000	.5367
3	5.0000	13.1598	5.0000	13.1597	6.0000	5.3157
4	36.6174	51.9049	-31.6177	-46.9049	5.3157	1.6321
5	27.2706	82.1113	-22.2706	-77.1114	5.3157	.5036
6	9.3470	48.7307	-22.2706	17.1131	1.6321	1.3018

RATIOS ARE

P2/P1=	40.7107	RHO2/1=	5.2507	T2/T1=	7.7534	A2/A1=	2.7845	U2/U1=	.2491
P3/P1=	2.0103	RHO3/1=	1.6306	T3/T1=	1.2328	A3/A1=	1.1103	U3/U1=	.9837
P4/P3=	20.2512	RHO4/3=	4.6667	T4/T3=	4.3395	A4/A3=	2.0831	U4/U3=	.6396
P5/P3=	32.1788	RHO5/3=	5.0833	T5/T3=	6.3303	A5/A3=	2.5160	U5/U3=	.2383
P6/P4=	1.5890	RHO6/4=	1.3881	T6/T4=	1.1448	A6/A4=	1.0699	U6/U4=	.8534
P4/P1=	40.7104	RHO4/1=	7.6096	T4/T1=	5.3499	A4/A1=	2.3130	U4/U1=	.6292
P5/P1=	64.6882	RHO5/1=	8.2888	T5/T1=	7.8043	A5/A1=	2.7936	U5/U1=	.2345
P6/P1=	64.6890	RHO6/1=	10.5626	T6/T1=	6.1243	A6/A1=	2.4747	U6/U1=	.5369

REGION	P PSI	RHO SLUGS/CU FT	T RANKINE	A FT/SEC	U FT/SEC	MU SLUG/FT-SEC	REYNOLDS NO 1/FT	MACH NO
1	.2533	1.93645E-04	109.7561	513.5679	3081.4074	8.46377E-08	7.05004E+06	6.0000
2	10.3138	1.01677E-03	850.9807	1430.0242	767.4385	5.36830E-07	1.45355E+06	.5367
3	.5093	3.15760E-04	135.3111	570.2302	3031.1919	1.06990E-07	8.94597E+06	5.3157
4	10.3138	1.47356E-03	587.1804	1187.8711	1938.7491	4.10988E-07	6.95122E+06	1.6321
5	16.3884	1.60509E-03	856.5663	1434.7097	722.4796	5.39255E-07	2.15046E+06	.5036
6	16.3886	2.04540E-03	672.1822	1270.9459	1654.5151	4.54249E-07	7.44998E+06	1.3018

STAGNATION CONDITIONS ARE

REGION	PSTAG PSIA	RHO SLUGS/CU FT	TSTAG RANKINE	PSTAG/PSTAG1
1	400.0000	3.72956E-02	900.0000	
2	12.5472	1.16958E-03	899.9981	.0314
3	386.5123	3.60290E-02	900.0088	.9663
4	45.9812	4.28605E-03	900.0088	.1150
5	19.4866	1.81641E-03	900.0088	.0487
6	45.5199	4.24305E-03	900.0088	.1138

CONDITIONS WITHOUT SHOCK INTERFERENCE ARE

WALL PRESSURE = 1.18604E+01 PSI
VELOCITY GRADIENT = 3.48123E+03 1/SEC
STAGNATION HEATING = 3.71299E+00 BTU/SQ.FT-SEC

CONDITIONS IN REGION 7

THETA = -1.28803E+01 DEG JET WIDTH = 3.95747E-02 FEET MACH NO. = 1.62535E+00 NOSE RADIUS = 3.68847E-02 FEET

WALL PRESSURE = 4.03125E+01 PSI
VELOCITY GRADIENT = 4.07153E+04 1/SEC
STAGNATION HEATING = 2.34103E+01 BTU/SQ.FT-SEC

RATIO NOSE RADIUS TO JET WIDTH = 1.26343E+01
P WALL/P PITOT FREE STREAM = 3.39893E+00
HEAT TRANSFER RATIO (WITH INTERFERENCE TO 3-D WITHOUT) = 6.30497E+00
HEAT TRANSFER RATIO(EDNEY) = 6.74970E+00

CONDITIONS IN REGICN 8

THETA = -3.48998E+00 DEG   JET WIDTH = 3.33868E-02 FEET   MACH NO. = 1.30180E+00   NOSE RADIUS = 1.82996E-02 FEET

WALL PRESSURE = 4.45667E+01 PSI
VELOCITY GRADIENT = 7.30754E+04 1/SEC
STAGNATION HEATING = 3.29761E+01 BTU/SQ.FT-SEC

RATIO NOSE RADIUS TO JET WIDTH = 1.49760E+01
P WALL/P PITOT FREE STREAM = 3.75762E+00
HEAT TRANSFER RATIO (WITH INTERFERENCE TO 3-D WITHOUT) = 8.88128E+00
HEAT TRANSFER RATIO(EDNEY) = 7.72665E+00

COORDINATES OF THE JET ARE

```
J1 ( 0.          , 0.          )
J2 ( 1.02482E-01,-1.09533E-01)
J3 ( 1.52770E-01,-9.40498E-02)
J4 ( 1.77751E-01,-1.40358E-01)
J5 ( 2.20376E-01,-1.09509E-01)
J6 ( 2.58936E-01,-1.45310E-01)
```

PART V - TYPE V INTERFERENCE

PROBLEM DISCUSSION

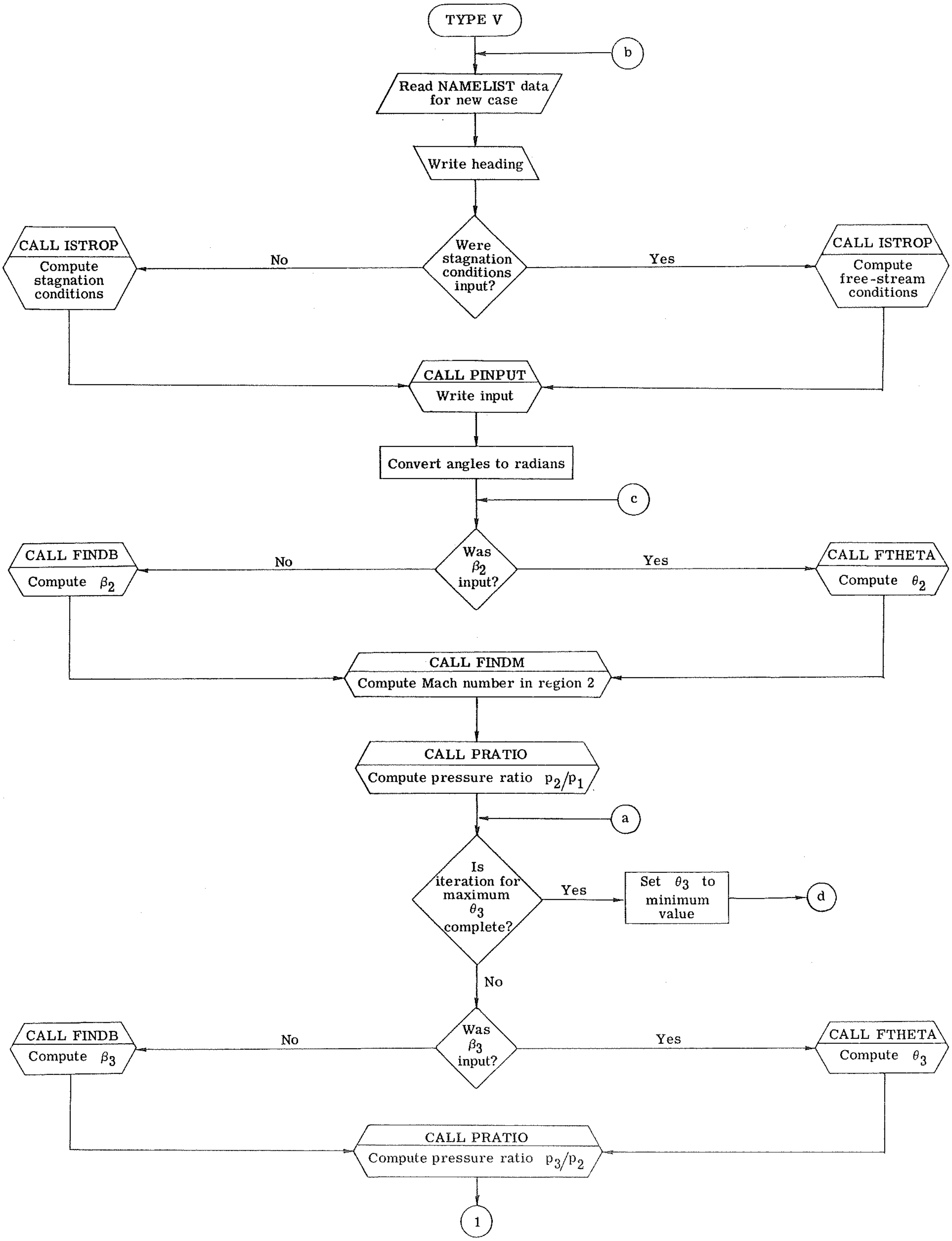
Type V interference involves the interaction of two weak shocks of the same family. The interaction produces a shear layer, a supersonic jet, and a transmitted impinging shock, as shown in figure 1(e). On a blunt body the shock interaction occurs near the upper sonic point, as shown in figure 2. A complete solution of the type V flow field shown in figure 9 is not presently available because of the embedded subsonic flow (region 4). It is possible, however, to follow the treatment for type II interference and solve only the supersonic regions adjacent to the body surface in order to obtain the peak values of pressure and heat transfer at the shock—boundary-layer interaction IP.

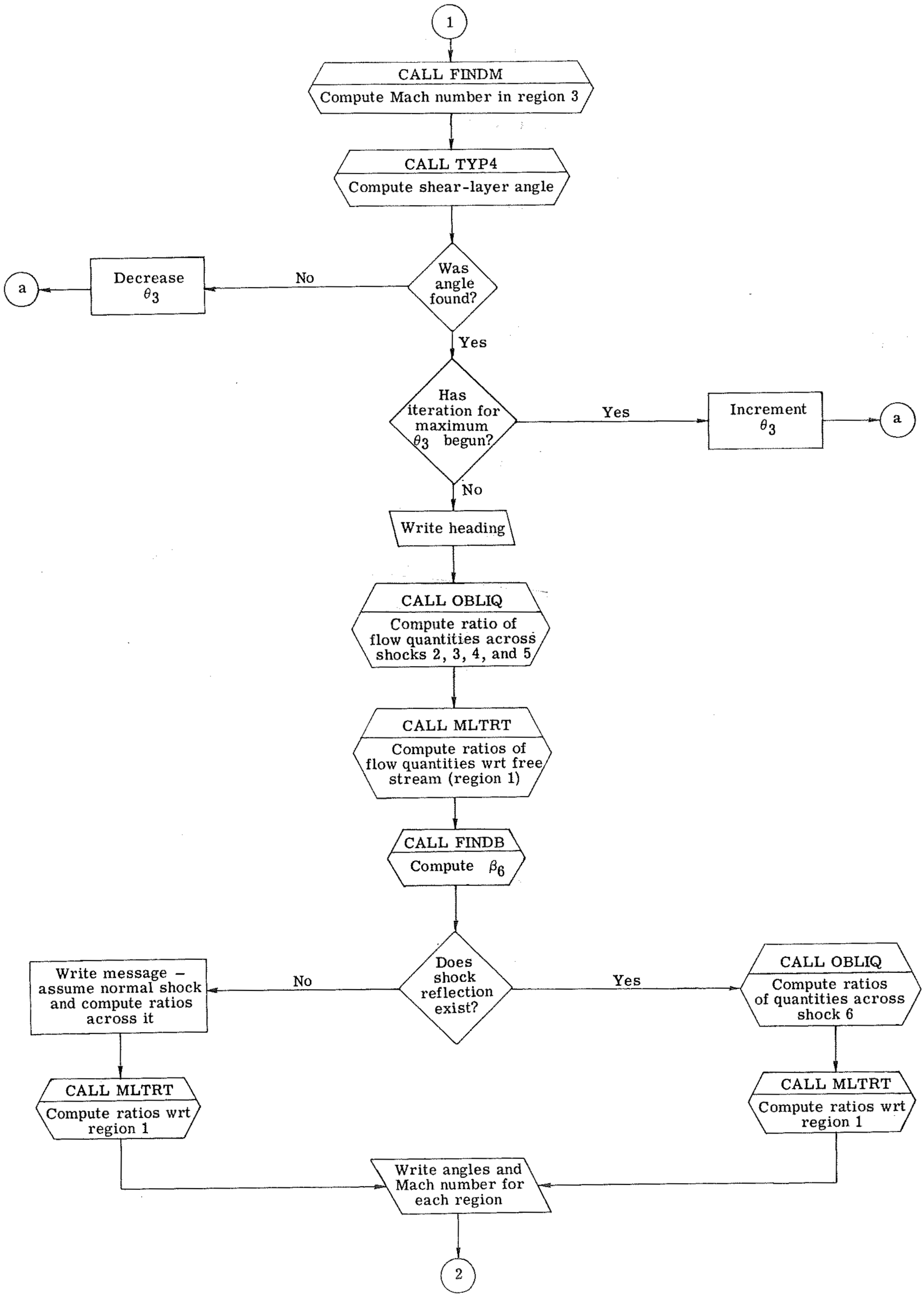
The method of solution for type V is similar to that for type II interference with the exception that the impinging shock is of the same family and directly influences the flow on the model. As in the case of types I and II, the flow model consisted of two wedges creating the bow and impinging shocks. The flow conditions in regions 2 and 3 are obtained by using the Rankine-Hugoniot equations once the free-stream conditions in region 1 and the flow angles (θ_i,θ_3) or shock angles (β_i,β_3) are specified. The triple-point configuration at point B is solved in the same manner as discussed in part II for a type II interference. The transmitted impinging shock may reflect as a shock or a Mach reflection depending on the Mach number in region 5 and the surface inclination. Once the pressure ratio across the shock—boundary-layer interaction p_6/p_3 is calculated and the state of the boundary layer and the impingement point are specified, the peak heating ratio is obtained from equation (1).

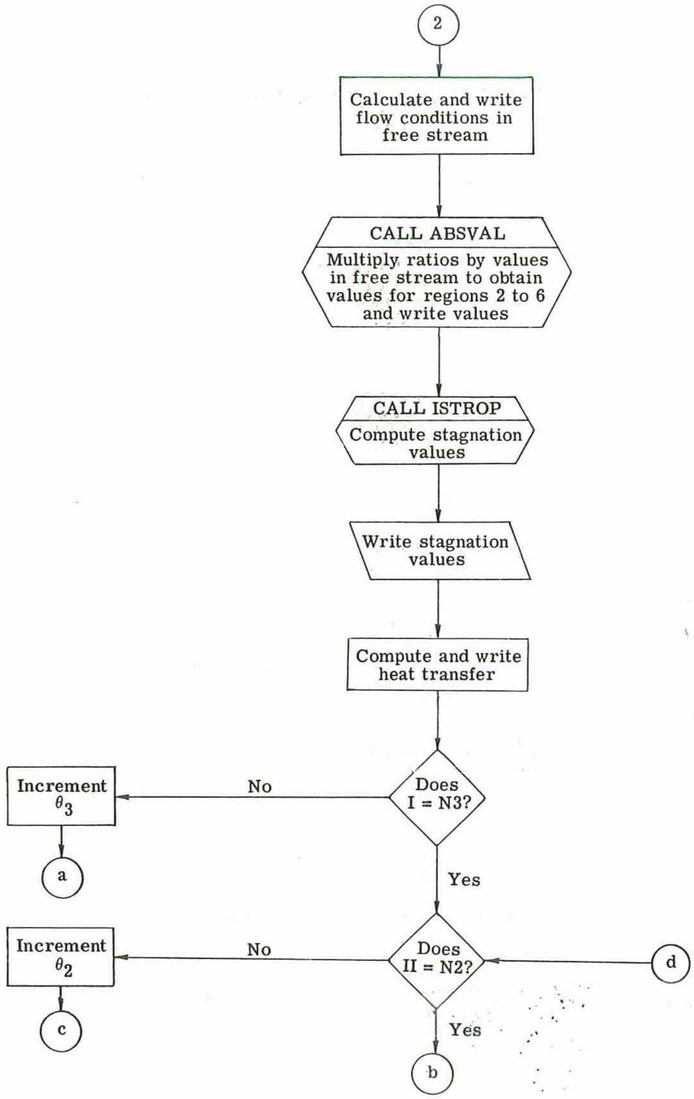
PROGRAM DESCRIPTION

The main program reads the input, calls the various subprograms, and computes the heat transfer. TYP4 calculates the flow deflection angle of the shear layer at point B (fig. 9). FTHETA is called to compute the flow angle and FINDB is called to compute the shock angles in each region. The subprograms OBLIQ, FINDM, PRATIO, MLTRT, ABSVAL, AND ISTROP compute flow variables and ratios of the flow variables. PINPUT prints the input variables. The flow charts and listings of these subprograms are presented in part VII. The flow diagram and listing for the main program follow.

Program Flow Chart – Main




1
CALL FINDM
Compute Mach number in region 3
CALL TYP4
Compute shear-layer angle
Was angle found?
No
Decrease θ_3
a
Yes
Has iteration for maximum θ_3 begun?
Yes
Increment θ_3
a
No
Write heading
CALL OBLIQ
Compute ratio of flow quantities across shocks 2, 3, 4, and 5
CALL MLTRT
Compute ratios of flow quantities wrt free stream (region 1)
CALL FINDB
Compute β_6
Does shock reflection exist?
No
Write message – assume normal shock and compute ratios across it
CALL MLTRT
Compute ratios wrt region 1
Yes
CALL OBLIQ
Compute ratios of quantities across shock 6
CALL MLTRT
Compute ratios wrt region 1
Write angles and Mach number for each region
2


2
Calculate and write flow conditions in free stream
CALL ABSVAL
Multiply ratios by values in free stream to obtain values for regions 2 to 6 and write values
CALL ISTROP
Compute stagnation values
Write stagnation values
Compute and write heat transfer
Does I = N3?
No
Increment θ_3
a
Yes
Does II = N2?
No
Increment θ_2
c
d
Yes
b

```
      PROGRAM SHOCK(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C     ..................................................................
C
C     THIS PROGRAM PERFORMS A TYPE V SHOCK INTERFERENCE PATTERN
C     FOR  TWO DIMENSIONAL FLOW
C
C     ..................................................................
      COMMON  PZ, RHOZ, TZ, P1OPZ, RHO1OZ, T1OTZ,
     1        PZ2, RHOZ2, TZ2, P2OPZ2, RHO2Z2, T2OTZ2,
     2        PZ3, RHOZ3, TZ3, P3OPZ3, RHO3Z3, T3OTZ3,
     3        PZ4, RHOZ4, TZ4, P4OPZ4, RHO4Z4, T4OTZ4,
     4        PZ5, RHOZ5, TZ5, P5OPZ5, RHO5Z5, T5OTZ5,
     5        PZ6, RHOZ6, TZ6, P6OPZ6, RHO6Z6, T6OTZ6,
     6        P2OP1, RHO2O1, T2OT1, A2OA1, U2OU1,
     7        P3OP2, RHO3O2, T3OT2, A3OA2, U3OU2,
     8        P3OP1, RHO3O1, T3OT1, A3OA1, U3OU1,
     9        P4OP2, RHO4O2, T4OT2, A4OA2, U4OU2,
     $        P4OP1, RHO4O1, T4OT1, A4OA1, U4OU1,
     $        P5OP3, RHO5O3, T5OT3, A5OA3, U5OU3,
     $        P6OP5, RHO6O5, T6OT5, A6OA5, U6OU5,
     $        P5OP1, RHO5O1, T5OT1, A5OA1, U5OU1,
     $        P6OP1, RHO6O1, T6OT1, A6OA1, U6OU1
      COMMON  P6OP3, RHO6O3, T6OT3, A6OA3, U6OU3
      COMMON  P1, RHO1, T1, A1, U1, VISC1, REY1,
     1        P2, RHO2, T2, A2, U2, VISC2, REY2,
     2        P3, RHO3, T3, A3, U3, VISC3, REY3,
     3        P4, RHO4, T4, A4, U4, VISC4, REY4,
     4        P5, RHO5, T5, A5, U5, VISC5, REY5,
     5        P6, RHO6, T6, A6, U6, VISC6, REY6
      DIMENSION T3STAR(2), RHO3STR(2), V3STAR(2), REY3STR(2), STN3(2), S
     1TN1(2), QFP(2), QPK(2), HFP(2), HPK(2), TR(2), RR(2), AA(2), RN(2)
      DIMENSION PN(2), HR(2)
C     SET DEFAULTS FOR INPUT VARIABLES
      DATA BETA/4HBETA/,TOL/.001/
      DATA TINCR/5.0/,TSTART/5.0/
      DATA GAMMA/1.4/,N2,N3,N6/1,1,1/,ANGLE2,ANGLE3/2*4HTHET/
      DATA IPT/0/,AMW/28.97/,TREF/532.98/,VREF/.3807E-6/,XL/1.0/
      DATA TWALL/530./,S/216./,CP/6006./,PR/.72/
      DATA TH2SV,BT2SV,TH3SV,BT3SV/4*0./,SVINCR/5.0/
      DATA AR/57.296/
C     ISW3 USED TO INDICATE ITERATION ON THETA3 HAS BEGUN
      NAMELIST /DATAIN/ RM1,GAMMA,THETA2,THETA3,TINCR,N2,N3,   TOL,ANGLE
     12,ANGLE3,BETA2,BETA3,IPT,T,P,AMW,TREF,VREF,XL,S,TWALL,CP,PR,RUN
C     SET CONSTANTS FOR STANTON NUMBERS
      ISW3=0
      SIGN=1.
      PN(1)=1.29
      PN(2)=0.85
      RN(1)=-.5
      RN(2)=-2.584
      AA(1)=0.332
      AA(2)=.185
      SIGN3=1.
C     ..................................................................
101   TINCR=SVINCR
      THETA3=TH3SV*57.296+TINCR
      BETA3=BT3SV*57.296+TINCR
      THETA2=TH2SV
      BETA2=BT2SV
```

```
      READ (5,DATAIN)
      IF (ENDFILE 5) 102,103
102   STOP
103   CONTINUE
      RR(1)=SQRT(PR)
      RR(2)=PR**(1./3.)
      WRITE (6,123) RUN
      R=1544.3/AMW
C     DENSITY(SLUG/CU FT)
      RHO=P*144./(32.2*R*T)
      IF (IPT) 104,104,105
C     STAGNATION CONDITIONS
104   TZ=T
      RHOZ=RHO
      PZ=P
      GO TO 106
C     FREE STREAM CONDITIONS
105   T1=T
      P1=P
      RHO1=RHO
106   CONTINUE
      CALL ISTROP (GAMMA,RM1,P1,PZ,P1OPZ,IPT)
C     PRINT OUT INPUT VARIABLES
      CALL PINPUT (RM1,GAMMA,IPT,T,P,AMW,TREF,VREF,XL,S,TWALL,CP,PR)
      WRITE (6,124) XL
      ITYP2=0
C     CONVERT ANGLES TO RADIANS
      TH2SV=THETA2
      BT2SV=BETA2
      SVINCR=TINCR
      TINCR=TINCR/57.296
      THETA2=THETA2/57.296-TINCR
      THETA3=THETA3/57.296-TINCR
      BETA2=BETA2/57.296-TINCR
      BETA3=BETA3/57.296-TINCR
      TH3SV=THETA3
      BT3SV=BETA3
      TINCR3=TINCR
C     ...............................................................
C     BEGIN DO LOOP TO INCREMENT THETA2
C     ...............................................................
      DO 121 II=1,N2
C     CALC NEEDED VALUES IN REGION 2
      IF (ANGLE2.NE.BETA) GO TO 107
      BETA2=BETA2+SIGN*TINCR
      THETA2=FTHETA(GAMMA,RM1,BETA2)
      GO TO 108
107   THETA2=THETA2+SIGN*TINCR
      IERROR=1
      BETA2=FINDB(GAMMA,RM1,THETA2,1,IERROR)
      IF (IERROR.GT.2) GO TO 122
108   SINB=SIN(BETA2)
      P2OP1=PRATIO(GAMMA,RM1,SINB)
      RM2=FINDM(GAMMA,RM1,SINB,BETA2,THETA2)
      THETA3=TH3SV-THETA2
      BETA3=BT3SV-THETA2
      ISW3=0
C     ...............................................................
C     BEGIN DO LOOP TO INCREMENT THETA3
C     ...............................................................
      DO 120 I=1,N3
      IF (ISW3.LT.0) GO TO 121
```

```
109   IF (ANGLE3.NE.BETA) GO TO 110
      BETA3=BETA3+SIGN3*TINCR3
      IF (BETA3.LT.0.) GO TO 120
      THETA3=FTHETA(GAMMA,RM2,BETA3)
      GO TO 111
110   THETA3=THETA3+SIGN3*TINCR3
      IF (THETA3.LT.0.) GO TO 120
      IERROR=1
      BETA3=FINDB(GAMMA,RM2,THETA3,1,IERROR)
      IF (IERROR.GT.2) GO TO 112
111   SINB=SIN(BETA3)
      T2DEG=THETA2*57.296
      T3DEG=THETA3*57.296+T2DEG
      P3OP2=PRATIO(GAMMA,RM2,SINB)
      RM3=FINDM(GAMMA,RM2,SINB,BETA3,THETA3)
C     ...................................................................
C
C     ITERATE ON THETAF UNTIL P5 = P4
C
C     ...................................................................
      THETAF=0.
      BETA4=1.5708
      IERROR=1
      CALL TYP4 (THETAF,BETA4,RM2,RM3,THETA3,THETA5,BETA5,P3OP2,GAMMA,TO
     1L,IERROR)
      IF (IERROR.GT.2) GO TO 112
      IF (ISW3.EQ.0) GO TO 114
C     ITERATION ON THETA3 HAS BEGUN.
C
C     INCREMENT THETA3
      TINCR3=TINCR3/2.
      SIGN3=1.
      IF (TINCR3.GT.TOL) GO TO 109
      ISW3=-1
      GO TO 114
C     DECREASE THETA3
112   TINCR3=TINCR3/2.
      SIGN3=-1.
      ISW3=1
      IF (TINCR3.GT.TOL) GO TO 109
      IF (TINCR3.LT.1.E-10) GO TO 113
      ISW3=-1
      GO TO 109
113   THDEG=THETA3*57.296
      J=3
      WRITE (6,140) J,THDEG,RM2,RM3
      GO TO 121
C     ...................................................................
C
C     CALC AND WRITE RATIOS FOR POINTS 1-5
C
C     ...................................................................
114   CONTINUE
      WRITE (6,125) T2DEG,T3DEG
      WRITE (6,132)
      IC=2
      CALL OBLIQ (GAMMA,RM1,THETA2,BETA2,RM2,P2OP1,1,2,IO)
      CALL OBLIQ (GAMMA,RM2,ABS(THETA3),BETA3,RM3,P3OP2,2,3,IO)
      IO=1
      CALL OBLIQ (GAMMA,RM2,ABS(THETAF),BETA4,RM4,P4OP2,2,4,IO)
      CALL OBLIQ (GAMMA,RM3,ABS(THETA5),BETA5,RM5,P5OP3,3,5,IO)
      CALL MLTRT (P3OP2,P2OP1,P3OP1,1,3,IO)
```

```
      CALL MLTRT (P40P2,P20P1,P40P1,1,4,IO)
      CALL MLTRT (P50P3,P30P1,P50P1,1,5,IO)
      THETA6=THETA5
      IERROR=1
      BETA6=FINDB(GAMMA,RM5,THETA6,1,IERROR)
      IF (IERROR.GT.2) GO TO 119
      ITYP2=4
C     CALC AND WRITE RATIOS FOR 6/5 AND 6/1
      IO=1
      CALL OBLIQ (GAMMA,RM5,THETA6,BETA6,RM6,P60P5,5,6,IO)
      CALL MLTRT (P60P5,P50P1,P60P1,1,6,IO)
      P60P3=P60P5*P50P3
115   CONTINUE
C     ...............................................................
C
C     PRINT RELATIVE, ABSOLUTE ANGLES AND MACH NUMBER AT POINTS 2-5
C
C     ...............................................................
      WRITE (6,133)
      THDEG=THETA2*AR
      BETDEG=BETA2*AR
      ABSTH=THDEG
      ABSBT=BETDEG
      J=2
      WRITE (6,134) J,THDEG,BETDEG,ABSTH,ABSBT,RM1,RM2
      THDEG=THETA3*AR
      BETDEG=BETA3*AR
      ABSTH=AR*(THETA3+THETA2)
      ABSBT=AR*(THETA2+BETA3)
      J=3
      WRITE (6,134) J,THDEG,BETDEG,ABSTH,ABSBT,RM2,RM3
      THETA4=THETAF
      THDEG=AR*THETA4
      IF (THETA4.LT.0) BETA4=3.14159-BETA4
      BETDEG=AR*BETA4
      ABSTH=AR*(THETA4+THETA2)
      ABSBT=AR*(BETA4+THETA2)
      J=4
      WRITE (6,134) J,THDEG,BETDEG,ABSTH,ABSBT,RM2,RM4
      THDEG=-AR*THETA5
      BETDEG=-AR*BETA5
      ABSTH=AR*(THETAF+THETA2)
      T5ABS=ABSTH
      ABSBT=AR*(THETA2+THETA3-BETA5)
      J=5
      WRITE (6,134) J,THDEG,BETDEG,ABSTH,ABSBT,RM3,RM5
C     PRINT THETA6 AND BETA6 IN REL AND-ABS DEGREES
      THDEG=THETA6*AR
      BETDEG=BETA6*AR
      ABSTH=T5ABS+AR*THETA6
      IF (BETA6.EQ.1.5708) GO TO 116
      ABSBT=T5ABS+AR*BETA6
      RM=RM5
      GO TO 117
116   RM=RM3
      ABSBT=ABSTH+BETDEG
117   J=6
      WRITE (6,134) J,THDEG,BETDEG,ABSTH,ABSBT,RM,RM6
C     ...............................................................
C
C     CALC AND WRITE ABSOLUTE VALUES FOR P,T,DENSITY,VEL,VISC,REYNOLDS
C
```

```
C     ..................................................................
      WRITE (6,135)
      WRITE (6,136)
      VISC1=VISCJ(VREF,TREF,T1,S)
      A1=SQRT(32.2*GAMMA*R*T1)
      U1=A1*RM1
      REY1=RHO1*U1/VISC1
      J=1
      WRITE (6,139) J,P1,RHO1,T1,A1,U1,VISC1,REY1,RM1
      IO=1
      J=2
      CALL ABSVAL (P2OP1,P1,P2,VREF,TREF,S,J,IO,RM2)
      J=3
      CALL ABSVAL (P3OP1,P1,P3,VREF,TREF,S,J,IO,RM3)
      J=4
      CALL ABSVAL (P4OP1,P1,P4,VREF,TREF,S,J,IO,RM4)
      J=5
      CALL ABSVAL (P5OP1,P1,P5,VREF,TREF,S,J,IO,RM5)
      J=6
      CALL ABSVAL (P6OP1,P1,P6,VREF,TREF,S,J,IO,RM6)
      WRITE (6,138)
      J=1
      WRITE (6,137) J,PZ,RHOZ,TZ
      CALL ISTROP (GAMMA,RM2,P2,PZ2,P3OPZ2,2)
      PZ2OZ=PZ2/PZ
      J=2
      WRITE (6,137) J,PZ2,RHOZ2,TZ2,PZ2OZ
      CALL ISTROP (GAMMA,RM3,P3,PZ3,P3OPZ3,3)
      PZ3OZ=PZ3/PZ
      J=3
      WRITE (6,137) J,PZ3,RHOZ3,TZ3,PZ3OZ
      CALL ISTROP (GAMMA,RM4,P4,PZ4,P4OPZ4,4)
      PZ4OZ=PZ4/PZ
      J=4
      WRITE (6,137) J,PZ4,RHOZ4,TZ4,PZ4OZ
      CALL ISTROP (GAMMA,RM5,P5,PZ5,P5OPZ5,5)
      PZ5OZ=PZ5/PZ
      J=5
      WRITE (6,137) J,PZ5,RHOZ5,TZ5,PZ5OZ
C     ..................................................................
C
C     CALCULATE AND WRITE STANTON NUMBER, FLAT PLATE HEAT TRANSFER
C     COEFFICIENT(HFP), AND HEATING RATE(QFP)  IN REGION 2
C
C     ..................................................................
C     J = 1 IS LAMINAR AND J=2 IS TURBULENT
      DO 118 J=1,2
C     RECOVERY TEMPERATURE
      TR(J)=T3+RR(J)*(TZ-T3)
C     ECKERT≠S REFERENCE TEMPERATURE
      T3STAR(J)=.5*(TWALL+T3)+.22*(TR(J)-T3)
      RHO3STR(J)=144.*P3/(32.2*R*T3STAR(J))
      V3STAR(J)=VISCJ(VREF,TREF,T3STAR,S)
      REY3STR(J)=RHO3STR(J)*U3*XL/V3STAR(J)
C     LOCAL INCOMPRESSIBLE STANTON NUMBER IN REGION 2 AT IMPINGEMENT
      CF2=AA(J)*REY3STR**RN(J)
      IF (J.EQ.2) CF2=AA(J)*ALOG10(REY3STR)**RN(J)
      STN3(J)=CF2*PR**(-2./3.)
C     COMPRESSIBLE FLAT PLATE HEAT TRANSFER COEF(BTU/SEC-FT2-R)
      HFP(J)=STN3(J)*RHO3STR*U3*CP/778.
C     FREE STREAM STANTON NUMBER
      STN1(J)=778.*HFP(J)/(RHO1*U1*CP)
```

```
C     FLAT PLATE HEATING RATE(BTU/SEC-FT2)
      QFP(J)=HFP(J)*(TR(J)-TWALL)
C     MARKARIAN HEAT TRANSFER RATIOS
      HR(J)=P6OP3**PN(J)
C     PEAK HEATING RATE
      QPK(J)=HR(J)*QFP(J)
C     PEAK HEAT TRANSFER COEF
118   HPK(J)=HFP(J)*HR(J)
      WRITE (6,126)
      WRITE (6,127) QFP(1),HFP(1),STN3(1),STN1(1),P6OP3,HR(1),QPK(1),HPK
     1(1)
      WRITE (6,128) QFP(2),HFP(2),STN3(2),STN1(2),P6OP3,HR(2),QPK(2),HPK
     1(2)
      WRITE (6,129)
C     ..........................................................
      GO TO 120
C     BECAUSE OBLIQUE REFLECTION NOT POSSIBLE BETWEEN 4 AND 6 USE NORMAL
C     SHOCK RELATIONS BETWEEN 6 AND 3
119   RM3SQ=RM3*RM3
      BETA6=1.5708
      WRITE (6,130)
      P6OP3=1.+2.*GAMMA/(GAMMA+1.)*(RM3SQ-1.)
      RHO6O3=(GAMMA+1.)*RM3SQ/((GAMMA-1.)*RM3SQ+2.)
      T6OT3=(2.*GAMMA*RM3SQ-(GAMMA-1.))*((GAMMA-1.)*RM3SQ+2.)
      T6OT3=T6OT3/((GAMMA+1.)**2*RM3SQ)
      A6OA3=ARATIO(T6OT3)
      RM6=SQRT(((GAMMA-1.)*RM3SQ+2.)/(2.*GAMMA*RM3SQ-(GAMMA-1.)))
      U6OU3=A6OA3*RM6/RM3
      WRITE (6,131) P6OP3,RHO6O3,T6OT3,A6OA3,U6OU3
      CALL MLTRT (P6OP3,P3OP1,P6OP1,1,6,IO)
      ISW6=-2
      GO TO 115
120   CONTINUE
C     HAVE FINISHED INCREMENTING THETA3
121   CONTINUE
C     HAVE FINISHED INCREMENTING THETA2
      GO TO 101
122   THDEG=THETA2*57.296
      J=2
      WRITE (6,140) J,THDEG,RM1
      GO TO 101
C
123   FORMAT (1H1,33H TYPE 5 SHOCK IMPINGEMENT PATTERN//11H RUN NUMBER,2
     1X,F5.2,/)
124   FORMAT (16H XL(WALL LENGTH),15X,F15.6,4H  FT)
125   FORMAT (1H1,20H INPUT VARIABLES ARE/8H THETA2=,F9.4,13H DEG, THETA
     13=,F9.4, 4H DEG)
126   FORMAT (//14H HEAT TRANSFER,/17X,1HQ,14X,3HHFP,12X,8HSTANTON3,7X,8
     1HSTANTON1,7X,5HP6/P3,10X,2HHR,12X,3HQPK,12X,3HHPK)
127   FORMAT (8H LAMINAR,2X,8(E15.5))
128   FORMAT (10H TURBULENT,8(E15.5))
129   FORMAT (1H0,41HHFP = HEAT TRANSFER COEF(BTU/SQ FT-SEC-R)/35H Q    =
     1 HEAT TRANSFER(BTU/SQ FT-SEC))
130   FORMAT (/1X,82HSHOCK REFLECTION NOT POSSIBLE AT THIS POINT - NORMA
     1L SHOCK BETWEEN 6 AND 3 ASSUMED/)
131   FORMAT (1X,6HP6/P3=,F8.4,5X,7HRHO6/3=,F8.4,5X,6HT6/T3=,F8.4,5X,6HA
     16/A3=,F8.4,5X,6HU6/U3=,F8.4)
132   FORMAT (//1X,10HRATIOS ARE/)
133   FORMAT (//12X,14HRELATIVE ANGLE,10X,14HABSOLUTE ANGLE,/9X,5HTHETA,
     18X,4HBETA,7X,5HTHETA,8X,4HBETA,30H  UPSTREAM MACH      LOCAL MACH)
134   FORMAT (1X,I1,4F12.4,2F15.4)
135   FORMAT (//7H REGION,11X,1HP,12X,3HRHO,11X,1HT,11X,1HA,11X,1HU,13X,
```

```
      12HMU,3X,11HREYNOLDS NO,9H  MACH NO)                               A 372
136   FORMAT (15X,3HPSI,4X,11HSLUGS/CU FT,5X,7HRANKINE,6X,6HFT/SEC,6X,6H A 373
     1FT/SEC,4X,11HSLUG/FT-SEC,11X,4H1/FT)                               A 374
137   FORMAT (1X,I5,F12.4,E15.5,3F12.4,2E15.5)                           A 375
138   FORMAT (/1X,25HSTAGNATION CONDITIONS ARE/7H REGION,11X,1HP,12X,3HR A 376
     1HO,11X,1HT,8X,4HP/PO/15X,3HPSI,4X,11HSLUGS/CU FT,5X,7HRANKINE)     A 377
139   FORMAT (1X,I5,F12.4,E15.5,3F12.4,2E15.5,F8.4)                      A 378
140   FORMAT (1H0,46HNO SOLUTION FOUND GIVEN THETA AND MACH NUMBER ,10HF A 379
     1OR REGION,I2,10X,3F10.4)                                           A 380
      END                                                                A 381-
C     ...............................................................    B   1
```

USAGE

Program SHOCK for a type V interference pattern uses the standard FORTRAN NAMELIST input with $DATAIN as the NAMELIST name. The input includes the flow conditions, gas properties, impinging flow deflection or shock angle, and impingement location on the body. The program can increment the shock generator angle and the body angle.

A description of the input and output variables and a sample case are presented.

Input Description

The $DATAIN input for type V is as follows:

RUN	run number for identification
RM1	M_∞, free-stream Mach number
GAMMA	c_p/c_v, ratio of specific heats
THETA2	θ_i, shock generator angle, deg
BETA2	β_i, impinging shock angle, deg
ANGLE2	THET if θ_i input; BETA if β_i input
THETA3	θ_b, body angle, deg
BETA3	β_b, bow shock angle, deg
ANGLE3	THET if θ_b input; BETA if β_b input

TINCR	increment for θ_2 and θ_b, deg
N2	number of times to increment θ_i
N3	number of times to increment θ_b
TOL	acceptable tolerance for equal pressures (0.001)
IPT	initial point; 0 for stagnation conditions, 1 for free-stream static conditions
T	temperature at IPT, $^{\circ}R$
P	pressure at IPT, psia
AMW	molecular weight (used to compute gas constant)
TREF	reference temperature for computing viscosity, $^{\circ}R$
VREF	reference viscosity for computing viscosity, slugs/ft-sec
XL	X_i, distance from leading edge to impingement point, ft
S	Sutherland's constant in viscosity equation
TWALL	temperature at wall, $^{\circ}R$
CP	c_p, specific heat at constant pressure, ft-lbf/slug-$^{\circ}R$
PR	N_{Pr}, Prandtl number

Output Description

The output consists of printing only. A heading and pertinent input are printed for identification before the calculations.

RUN NUMBER	run number for identification
M1	M_∞, Mach number in free stream

GAMMA (CP/CV)	ratio of specific heats
TEMP AT POINT "IPT"	input as T, ^{o}R
PRES AT POINT "IPT"	input as P, psia
MOLECULAR WEIGHT	molecular weight (used to compute gas constant)
REFERENCE TEMP	reference temperature for computing viscosity, ^{o}R
REFERENCE VISCOSITY	reference viscosity for computing viscosity, slugs/ft-sec
S(SUTHERLAND NUMBER)	Sutherland's constant in viscosity equation
TEMP AT WALL	T_w, ^{o}R
CP	c_p, specific heat at constant pressure, ft-lbf/slug-^{o}R
PRANDTL NUMBER	N_{Pr}, Prandtl number
XL(WALL LENGTH)	X_i, length from leading edge to impingement point, ft
THETA2	θ_i, shock generator angle, deg
THETA3	θ_b, body angle, deg
P2/P1, etc.	p_2/p_1, etc., pressure ratios for regions listed
RHO2/1, etc.	ρ_2/ρ_1, etc., density ratios for regions listed
T2/T1, etc.	T_2/T_1, etc., temperature ratios for regions listed
A2/A1, etc.	a_2/a_1, etc., ratios of speeds of sound in regions listed
U2/U1, etc.	u_2/u_1, etc., velocity ratios for regions listed
RELATIVE ANGLE	
THETA	flow angle relative to flow in upstream region, deg

BETA	shock angle relative to flow in upstream region, deg
ABSOLUTE ANGLE	
THETA	flow angle relative to free-stream flow, deg
BETA	shock angle relative to free-stream flow, deg
UPSTREAM MACH	Mach number in upstream region
LOCAL MACH	local Mach number
REGION	region in shock pattern
P	static pressure in region, psia
RHO	static density in region, slugs/ft^3
T	static temperature in region, ^{o}R
A	speed of sound in region, ft/sec
U	velocity in region, ft/sec
MU	static viscosity in region, slugs/ft-sec
REYNOLDS NO	Reynolds number per foot in region
MACH NO	Mach number in region

The following stagnation conditions are then listed:

P	total pressure in region, psia
RHO	total density in region, slugs/ft^3
T	total temperature in region
P/P0	ratio of total pressure in region to free-stream total pressure

The peak pressure ratio and heat transfer for laminar and turbulent flow are listed as

Q	heat-transfer rate, Btu/ft^2-sec
HFP	flat-plate heat-transfer coefficient, Btu/ft^2-sec-^{o}R
STANTON3	local incompressible Stanton number
STANTON1	compressible free-stream Stanton number
P6/P3	peak pressure ratio
HR	Markarian heat-transfer ratio
QPK	peak heating rate
HPK	peak heat-transfer coefficient

Sample Case – Input

```
$DATAIN
RM1     =  0.6E+01,
GAMMA   =  0.14E+01,
THETA2  =  0.5E+01,
THETA3  =  0.35E+02,
TINCR   =  0.5E+01,
N2      =  1,
N3      =  1,
TOL     =  0.1E-02,
ANGLE2  =  0.69404725765109E+93,
ANGLE3  =  0.69404725765109E+93,
BETA2   =  0.0,
BETA3   =  0.5E+01,
IPT     =  0,
```

```
T          =  0.9E+03,
P          =  0.4E+03,
AMW        =  0.2897E+02,
TREF       =  0.53E+03,
VREF       =  0.3801E-06,
XL         =  0.25E+00,
S          =  0.1986E+03,
TWALL      =  0.55E+03,
CP         =  0.6006E+04,
PR         =  0.72E+00,
RUN        =  0.1E+01,
$END
```

Sample Case – Output

```
 TYPE 5 SHOCK IMPINGEMENT PATTERN

RUN NUMBER    1.00


INPUT VARIABLES ARE

M1                                        6.000
GAMMA(CP/CV)                              1.400000
TEMP AT POINT 0                         900.000000   RANKINE
PRES AT POINT 0                         400.000000   PSI
MOLECULAR WEIGHT                         28.970000
REFERENCE TEMP                          530.000000   RANKINE
REFERENCE VISCOSITY                    3.801000E-07  SLUG/(FT-SEC)
S(SUTHERLAND NUMBER)                    198.600
TEMP AT WALL                            550.000      RANKINE
CP                                     6006.000      FT-LBF/(SLUG-RANKINE)
PRANDTL NUMBER                            .720000
XL(WALL LENGTH)                           .250000    FT
```

INPUT VARIABLES ARE
THETA2= 5.0000 DEG, THETA3= 35.0000 DEG

RATIOS ARE

P2/P1= 2.0103	RH02/1= 1.6306	T2/T1= 1.2328	A2/A1= 1.1103	U2/U1= .9837
P3/P2= 14.4557	RH03/2= 4.2890	T3/T2= 3.3704	A3/A2= 1.8359	U3/U2= .7619
P4/P2= 32.6463	RH04/2= 5.0944	T4/T2= 6.4083	A4/A2= 2.5315	U4/U2= .2074
P5/P3= 2.2584	RH05/3= 1.7619	T5/T3= 1.2818	A5/A3= 1.1322	U5/U3= .8429
P3/P1= 29.0599	RH03/1= 6.9937	T3/T1= 4.1552	A3/A1= 2.0384	U3/U1= .7495
P4/P1= 65.6280	RH04/1= 8.3069	T4/T1= 7.9004	A4/A1= 2.8108	U4/U1= .2040
P5/P1= 65.6287	RH05/1= 12.3221	T5/T1= 5.3261	A5/A1= 2.3078	U5/U1= .6318
P6/P5= 2.1516	RH06/5= 1.7064	T6/T5= 1.2609	A6/A5= 1.1229	U6/U5= .7186
P6/P1=141.2090	RH06/1= 21.0261	T6/T1= 6.7159	A6/A1= 2.5915	U6/U1= .4540

	RELATIVE ANGLE		ABSOLUTE ANGLE			
	THETA	BETA	THETA	BETA	UPSTREAM MACH	LOCAL MACH
2	5.0000	13.1598	5.0000	13.1598	6.0000	5.3157
3	30.0000	41.7590	35.0000	46.7590	5.3157	2.2062
4	15.2998	86.0870	20.2998	91.0870	5.3157	.4355
5	-14.7002	-40.8059	20.2998	-5.8059	2.2062	1.6426
6	14.7002	59.1159	35.0000	79.4157	1.6426	1.0512

REGION	P	RHO	T	A	U	MU	REYNOLDS NO	MACH NO
	PSI	SLUGS/CU FT	RANKINE	FT/SEC	FT/SEC	SLUG/FT-SEC	1/FT	
1	.2533	1.93645E-04	109.7561	513.5679	3081.4074	8.46377E-08	7.05004E+06	6.0000
2	.5093	3.15760E-04	135.3111	570.2302	3031.1919	1.06990E-07	8.94597E+06	5.3157
3	7.3622	1.35425E-03	456.0559	1046.8696	2309.6012	3.37666E-07	9.26320E+06	2.2062
4	16.6265	1.60859E-03	867.1188	1443.5201	628.6374	5.43812E-07	1.85950E+06	.4355
5	16.6267	2.38610E-03	584.5741	1185.2319	1946.8091	4.09613E-07	1.13407E+07	1.6426
6	35.7745	4.07161E-03	737.1088	1330.9120	1399.0370	4.85434E-07	1.17345E+07	1.0512

STAGNATION CONDITIONS ARE

REGION	P	RHO	T	P/PO
	PSI	SLUGS/CU FT	RANKINE	
1	400.0000	3.72856E-02	900.0000	
2	386.5123	3.60280E-02	900.0088	.9663
3	79.4888	7.40940E-03	900.0089	.1987
4	18.9404	1.76549E-03	900.0088	.0474
5	75.2889	7.01791E-03	900.0089	.1882

HEAT TRANSFER

	Q	HFP	STANTON3	STANTON1	P6/P3	HR	QPK	HPK
LAMINAR	1.80333E+00	6.37771E-03	3.39326E-04	1.38453E-03	4.85924E+00	7.68551E+00	1.38595E+01	4.90159E-02
TURBULENT	1.19347E+01	3.92648E-02	2.08909E-03	8.52398E-03	4.85924E+00	3.83339E+00	4.57504E+01	1.50517E-01

HFP = HEAT TRANSFER COEF(BTU/SQ FT-SEC-R)
Q = HEAT TRANSFER(BTU/SQ FT-SEC)

PART VI – TYPE VI INTERFERENCE

PROBLEM DISCUSSION

Type VI interference involves the intersection of two weak shocks of the same family, which leads to the entirely supersonic flow field shown in figures 1(f) and 10. The expansion fan emanating from this intersection interacts with the boundary layer at IP and results in a local decrease in pressure and heating. A study of this type of interference is important because it provides a means for predicting the onset of type V, which does lead to significant increases in local heating.

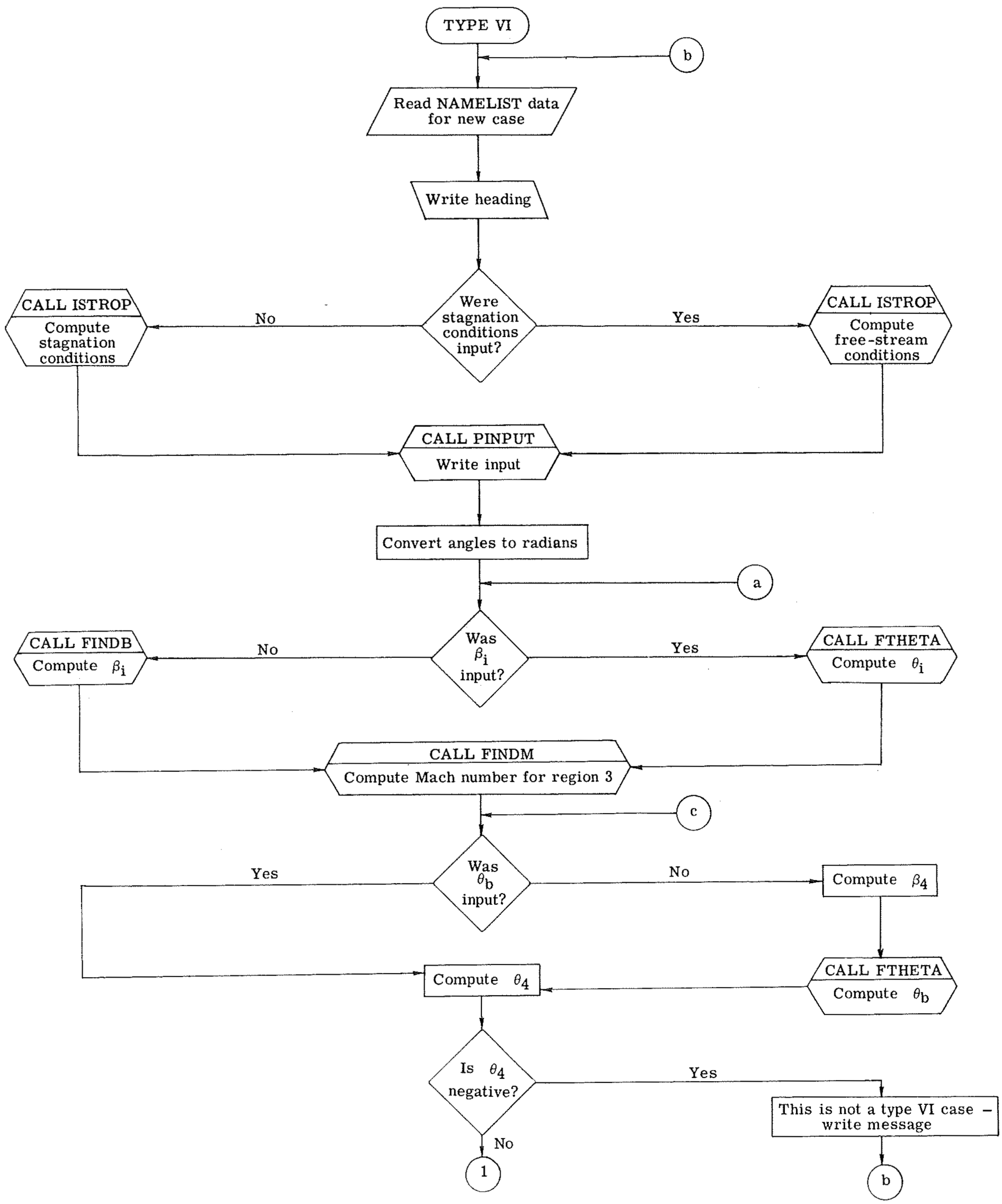
The flow conditions in region 3 are determined by using the oblique-shock relations of reference 6 and the specified free-stream conditions and flow angle θ_i or shock angle β_i, in a manner similar to that for type I. Once the body angle θ_b is specified, the flow in region 4 is calculated. An iterative scheme is used to determine the location of the bow shock that separates regions 1 and 2 so as to satisfy continuity of the pressures and flow direction across the shear layer between regions 2 and 5. The flow from region 4 must pass through an expansion fan to turn parallel to the shear layer. The relations for a Prandtl-Meyer expansion from reference 6 are used in the above iteration to go from region 4 to region 5. In order to turn parallel with the surface, the flow passes through a series of reflected expansion waves in going from region 5 to region 6. For low Mach numbers and small turning angles, the total reduction in pressure from region 4 to region 6 at the wall is approximately twice the decrease across the first expansion fan. (See p. 451 of ref. 7.)

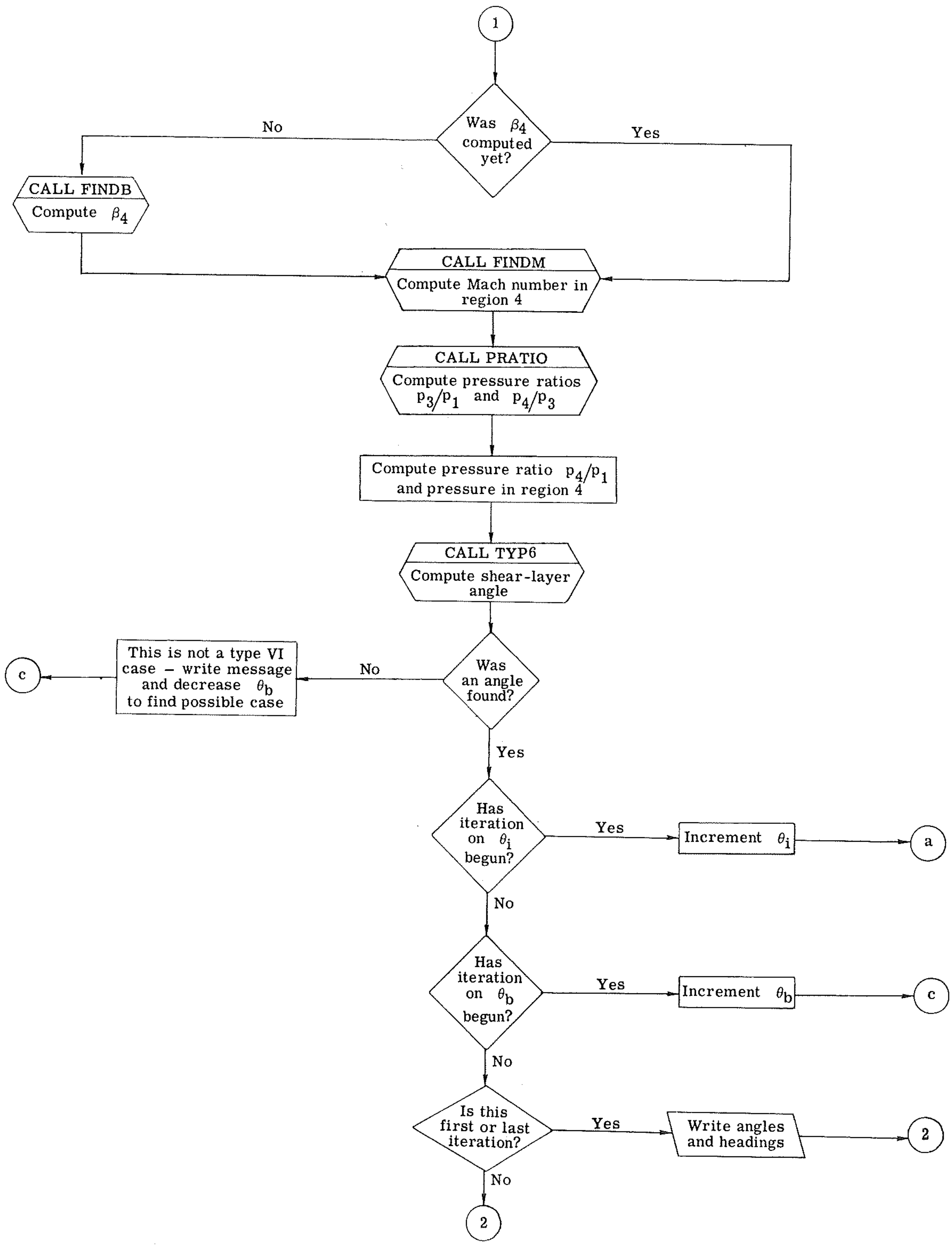
The heat-transfer relation (eq. (1)) is used to calculate the reduction in heating with p_6/p_4 used as the pressure ratio. This expression can be used since it has been shown in references 2 and 19 that the equation gives good predictions of the heating reduction for laminar and turbulent expansion-fan—boundary-layer interactions.

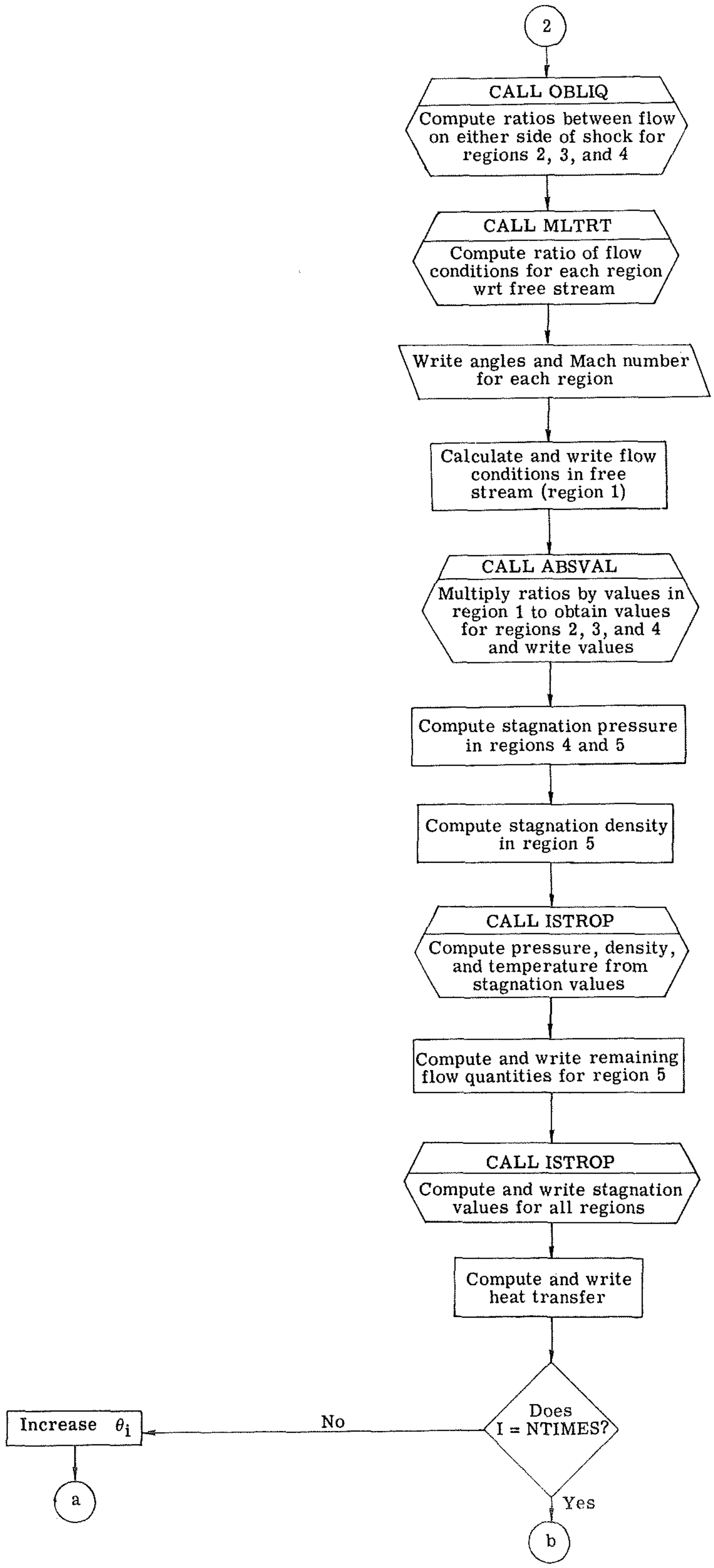
PROGRAM DESCRIPTION

The main program reads the input, calls the various subprograms, and computes the heat transfer. FTHETA is called to compute the flow angle and FINDB is called to compute the shock angles in each region. The subprograms OBLIQ, FINDM, PRATIO, MLTRT, ABSVAL, and ISTROP compute flow variables and ratios of the flow variables. PINPUT prints the input variables. The flow charts and listings of these subprograms are presented in part VII. TYP6 using EXPNS calculates the deflection angle of the shear layer. The flow diagrams and listings for the main program, TYP6, and EXPNS follow.

Program Flow Chart – Main




1
Was β_4 computed yet?
No
Yes
CALL FINDB
Compute β_4
CALL FINDM
Compute Mach number in region 4
CALL PRATIO
Compute pressure ratios p_3/p_1 and p_4/p_3
Compute pressure ratio p_4/p_1 and pressure in region 4
CALL TYP6
Compute shear-layer angle
Was an angle found?
No
This is not a type VI case – write message and decrease θ_b to find possible case
c
Yes
Has iteration on θ_i begun?
Yes
Increment θ_i
a
No
Has iteration on θ_b begun?
Yes
Increment θ_b
c
No
Is this first or last iteration?
Yes
Write angles and headings
2
No
2


2
CALL OBLIQ
Compute ratios between flow on either side of shock for regions 2, 3, and 4
CALL MLTRT
Compute ratio of flow conditions for each region wrt free stream
Write angles and Mach number for each region
Calculate and write flow conditions in free stream (region 1)
CALL ABSVAL
Multiply ratios by values in region 1 to obtain values for regions 2, 3, and 4 and write values
Compute stagnation pressure in regions 4 and 5
Compute stagnation density in region 5
CALL ISTROP
Compute pressure, density, and temperature from stagnation values
Compute and write remaining flow quantities for region 5
CALL ISTROP
Compute and write stagnation values for all regions
Compute and write heat transfer
Does I = NTIMES?
No
Increase θ_i
a
Yes
b

```
      PROGRAM SHOCK(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C     ..............................................................
C
C     PURPOSE
C     THIS PROGRAM PERFORMS A TYPE VI SHOCK INTERFERENCE PATTERN
C     FOR  TWO DIMENSIONAL FLOW
C
C     ..............................................................
      COMMON  PZ, RHOZ, TZ, P1OPZ, RHO1OZ, T1OTZ,
     1        PZ2, RHOZ2, TZ2, P2OPZ2, RHO2Z2, T2CTZ2,
     2        PZ3, RHOZ3, TZ3, P3OPZ3, RHO3Z3, T3OTZ3,
     3        PZ4, RHOZ4, TZ4, P4OPZ4, RHO4Z4, T4CTZ4,
     4        PZ5, RHOZ5, TZ5, P5OPZ5, RHO5Z5, T5CTZ5,
     5        P2OP1, RHO2C1, T2OT1, A2OA1, U2OU1,
     6        P3OP1, RHO3O1, T3OT1, A3CA1, U3OU1,
     7        P4OP3, RHO4O3, T4OT3, A4OA3, U4OU3,
     8        P4OP1, RHO4O1, T4OT1, A4CA1, U4OU1,
     9        P5OP4, RHO5O4, T5OT4, A5OA4, U5OU4,
     $        P5OP1, RHO5O1, T5OT1, A5OA1, U5OU1,
     $        P1, RHO1, T1, A1, U1, VISC1, REY1,
     $        P2, RHO2, T2, A2, U2, VISC2, REY2,
     $        P3, RHO3, T3, A3, U3, VISC3, REY3,
     $        P4, RHO4, T4, A4, U4, VISC4, REY4,
     $        P5, RHO5, T5, A5, U5, VISC5, REY5
      DIMENSION T4STAR(2), RHO4STR(2), V4STAR(2), REY4STR(2), HR(2), QFP
     1(2), HPK(2), QPK(2), STN4(2)
      DIMENSION STN1(2)
      DIMENSION PN(2)
      DIMENSION AA(2), RN(2)
      DIMENSION RR(2), TR(2), HFP(2)
      NAMELIST /DATAIN/ RM1,GAMMA,THETAB,THETAI,TINCR,NTIMES,IPT,T,P,AMW
     1,TREF,VREF,XL,S,TWALL,CP,PR,RUN,ANGLE,ANGLE2,TOL
C     SET CONSTANTS FOR STANTON NUMBERS
      BETA=4HBETA
      PN(1)=1.29
      PN(2)=0.85
      AA(1)=0.332
      AA(2)=.185
      RN(1)=-.5
      RN(2)=-2.584
C     CONVERGENCE TEST FOR THETAF
      TOL=.001
      NTIMES=1
      TINCR=5.
C     ..............................................................
C
C     INPUT DATA
C
C     ..............................................................
  101 READ (5,DATAIN)
      IF (ENDFILE 5) 102,103
  102 STOP
  103 CONTINUE
      WRITE(6,DATAIN)
      RR(1)=SQRT(PR)
      RR(2)=PR**(1./3.)
      WRITE (6,133) RUN
      THBDEG=THETAB
      THFDEG=THETAI
```

```
      THIFST=THIDEG
      SINCR=TINCR
C     GAS CONSTANT(FT-LBF/LBM-R)
      R=1544.3/AMW
C     DENSITY(SLUG/CU FT)
      RHO=P*144./(32.2*R*T)
      IF (IPT) 104,104,105
C     STAGNATION CONDITIONS
104   TZ=T
      RHOZ=RHO
      PZ=P
      GO TO 106
C     FREE STREAM CONDITIONS
105   T1=T
      P1=P
      RHO1=RHO
C     GO ISENTROPICALLY TO EITHER FREE STREAM OR TO STAGNATION
106   CALL ISTROP (GAMMA,RM1,P1,PZ,P1OPZ,IPT)
C     PRINT OUT INPUT VARIABLES
      CALL PINPUT (RM1,GAMMA,IPT,T,P,AMW,TREF,VREF,XL,S,TWALL,CP,PR)
C     CONVERT ANGLES TO RADIANS
      TINCR=TINCR/57.296
      THETAB=THBDEG/57.296
      THETAI=THETAI/57.296
      INPBI=0
      INPBB=0
      ISW=0
      DO 113 I=1,NTIMES
C     BETAI WAS INPUT INSTEAD OF THETAI
      IF (ANGLE.NE.BETA) GO TO 107
      BETAI=THETAI
      INPBI=1
      THETAI=FTHETA(GAMMA,RM1,BETAI)
107   THIDEG=THETAI*57.296
C     WAS BETAI INPUT
      IF (INPBI.GT.0) GO TO 108
      BETAI=FINDB(GAMMA,RM1,THETAI,1,IERROR)
C     THETAI TOO LARGE
      IF (IERROR.GT.2) GO TO 121
108   RM3=FINDM(GAMMA,RM1,SIN(BETAI),BETAI,THETAI)
      IF (ANGLE2.NE.BETA) GO TO 109
C     BETAB WAS INPUT INSTEAD OF THETAB
      BETA4=+THBDEG/57.296-THETAI
      INPBB=1
      THETAB=FTHETA(GAMMA,RM3,ABS(BETA4))+THETAI
109   CONTINUE
      THDEG=THETAB*57.296
C     ...............................................................
C
C     ITERATE ON THETAF UNTIL P2=P5
C
C     ...............................................................
      THETA4=THETAB-THETAI
C     INPUT ERROR IF THETA4 NEGATIVE
      IF (THETA4.LT.0) GO TO 123
      IF (INPBB.GT.0) GO TO 110
      BETA4=FINDB(GAMMA,RM3,THETA4,1,IERROR)
C     THETA4 TOO LARGE
      IF (IERROR.GT.2) GO TO 122
110   RM4=FINDM(GAMMA,RM3,SIN(BETA4),BETA4,THETA4)
      P3OP1=PRATIO(GAMMA,RM1,SIN(BETAI))
      P4OP3=PRATIO(GAMMA,RM3,SIN(BETA4))
```

```
      P4OP1=P4OP3*P3OP1
      P4=P4OP1*P1
      CALL TYP6 (THETAF,BETA2,RM1,RM4,RM5,THETAB,P1,P4,P5,GAMMA,TOL,IERR
     1OR,OPTION,P2S01)
C     WAS A SOLUTION FOUND
      IF (IERROR) 111,111,115
C     HAS ITERATION ON THETAI BEGUN
111   IF (ISW.EQ.1) GO TO 119
C     HAS ITERATION ON THETAB BEGUN
      IF (ISW.EQ.2) GO TO 116
      IF (ISW.LE.0) WRITE (6,134)
      IF (ISW.LE.0) WRITE (6,135) THIDEG,THDEG
C     ..................................................................
C
C     CALCULATE AND WRITE PARAMETER RATIOS FOR 2/1, 3/1, 4/3, 4/1
C
C     ..................................................................
      IO=2
      WRITE (6,124)
      THETA2=ABS(THETAF)
      CALL OBLIQ (GAMMA,RM1,ABS(THETA2),BETA2,RM2,P2OP1,1,2,IO/2)
      CALL OBLIQ (GAMMA,RM1,THETAI,BETAI,RM3,P3OP1,1,3,IO)
      CALL OBLIQ (GAMMA,RM3,THETA4,BETA4,RM4,P4OP3,3,4,IO)
      CALL MLTRT (P4OP3,P3OP1,P4OP1,1,4,1)
C     ..................................................................
C
C               WRITE THETA AND BETA ANGLES AND MACH NUMBER
C
C     ..................................................................
      WRITE (6,125)
      THFDEG=THETAF*57.296
      THETA2=THETAF
      THDEG=THETA2*180./3.1416
      BETDEG=BETA2*180./3.1416
      ABSTH=THFDEG
      ABSBT=BETDEG
      J=2
      WRITE (6,138) J,THDEG,BETDEG,ABSTH,ABSBT,RM1,RM2
      THDEG=THETAI*57.296
      BETDEG=BETAI*57.296
      ABSTH=THIDEG
      ABSBT=BETDEG
      J=3
      WRITE (6,138) J,THDEG,BETDEG,ABSTH,ABSBT,RM1,RM3
      THDEG=THETA4*57.296
      BETDEG=BETA4*57.296
      ABSTH=THETAB*57.296
      ABSBT=BETDEG+THIDEG
      J=4
      WRITE (6,138) J,THDEG,BETDEG,ABSTH,ABSBT,RM3,RM4
      THDEG=(THETAF-THETA4)*57.296
      ABSTH=THETAF*57.296
      J=5
      WRITE (6,138) J,THDEG,BETDEG,ABSTH,ABSBT,RM4,RM5
C     ..................................................................
C
C     CALCULATE ABSOLUTE VALUES FOR POINTS 0 THRU 4
C
C     ..................................................................
      WRITE (6,126)
      WRITE (6,127)
      VISC1=VISCJ(VREF,TREF,T1,S)
```

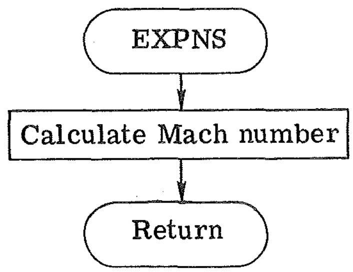
```
      A1=SQRT(32.2*GAMMA*R*T1)
      U1=A1*RM1
      REY1=RHO1*U1/VISC1
      J=1
      WRITE (6,128) J,P1,RHO1,T1,A1,U1,VISC1,REY1,RM1
      IO=1
      J=2
      CALL ABSVAL (P2OP1,P1,P2,VREF,TREF,S,J,IO,RM2)
      J=3
      CALL ABSVAL (P3OP1,P1,P3,VREF,TREF,S,J,IO,RM3)
      J=4
      CALL ABSVAL (P4OP1,P1,P4,VREF,TREF,S,J,IO,RM4)
      PZ4O4=(1.+(GAMMA-1.)*RM4*RM4/2.)**(GAMMA/(GAMMA-1.))
      PZ4=PZ4O4*P4
      PZ5=PZ4
      TZ5=TZ
      RHOZ5=PZ4*144./(32.2*R*TZ)
      CALL ISTROP (GAMMA,RM5,P5,PZ5,P5OPZ5,0)
      VISC5=VISCJ(VREF,TREF,T5,S)
      A5=SQRT(32.2*GAMMA*R*T5)
      U5=A5*RM5
      REY5=RHO5*U5/VISC5
      J=5
      WRITE (6,128) J,P5,RHO5,T5,A5,U5,VISC5,REY5,RM5
      WRITE (6,129)
      J=1
      WRITE (6,128) J,PZ,RHOZ,TZ
      J=2
      CALL ISTROP (GAMMA,RM2,P2,PZ2,P2OPZ2,2)
      PZ2OZ=PZ2/PZ
      WRITE (6,128) J,PZ2,RHOZ2,TZ2,PZ2OZ
      J=3
      CALL ISTROP (GAMMA,RM3,P3,PZ3,P3OPZ3,3)
      PZ3OZ=PZ3/PZ
      WRITE (6,128) J,PZ3,RHOZ3,TZ3,PZ3OZ
      J=4
      CALL ISTROP (GAMMA,RM4,P4,PZ4,P4OPZ4,4)
      PZ4OZ=PZ4/PZ
      WRITE (6,128) J,PZ4,RHOZ4,TZ4,PZ4OZ
      J=5
      PZ5OZ=PZ5/PZ
      WRITE (6,128) J,PZ5,RHOZ5,TZ5,PZ5OZ
      P5OP4=P5/P4
C     PRESSURE DROP FOR REGION 6 IS SAME AS FOR REGION 5
      P6OP4=2.0*P5OP4-1.0
C     ..............................................................
C
C     CALCULATE AND WRITE STANTON NUMBER, FLAT PLATE HEAT TRANSFER
C     COEFFICIENT(HFP), AND HEATING RATE(QFP)  IN REGION 4
C
C     ..............................................................
C     J = 1 IS LAMINAR AND J=2 IS TURBULENT
      DO 112 J=1,2
C     RECOVERY TEMPERATURE
      TR(J)=T4+RR(J)*(TZ-T4)
C     ECKERT≠S REFERENCE TEMPERATURE
      T4STAR(J)=.5*(TWALL+T2)+.22*(TR(J)-T2)
      RHO4STR(J)=144.*P4/(32.2*R*T4STAR(J))
      V4STAR(J)=VISCJ(VREF,TREF,T4STAR,S)
      REY4STR(J)=RHO4STR(J)*U4*XL/V4STAR(J)
C     LOCAL INCOMPRESSIBLE STANTON NUMBER IN REGION 4 AT IMPINGEMENT
      CF2=AA(J)*REY4STR**RN(J)
```

```
      IF (J.EQ.2) CF2=AA(J)*ALOG10(REY4STR)**RN(J)
      STN4(J)=CF2*PR**(-2./3.)
C     COMPRESSIBLE FLAT PLATE HEAT TRANSFER COEF(BTU/SEC-FT2-R)
      HFP(J)=STN4(J)*RHO4STR*U4*CP/778.
C     FREE STREAM STANTON NUMBER
      STN1(J)=778.*HFP(J)/(RHO1*U1*CP)
C     FLAT PLATE HEATING RATE(BTU/SEC-FT2)
      QFP(J)=HFP(J)*(TR(J)-TWALL)
C     MARKARIAN HEAT TRANSFER RATIOS
      HR(J)=P60P4**PN(J)
C     PEAK HEATING RATE
      QPK(J)=HR(J)*QFP(J)
C     PEAK HEAT TRANSFER COEF
112   HPK(J)=HFP(J)*HR(J)
      WRITE (6,130)
      WRITE (6,131) QFP(1),HFP(1),STN4(1),STN1(1),P60P4,HR(1),QPK(1),HPK
     1(1)
      WRITE (6,132) QFP(2),HFP(2),STN4(2),STN1(2),P60P4,HR(2),QPK(2),HPK
     1(2)
      IF (ISW.LT.0) GO TO 114
113   THETAI=THETAI+TINCR
C     RESTORE THETAI TO STARTING VALUE
114   THIDEG=THIFST
      TINCR=SINCR
      GO TO 101
C     NO TYPE 6 SOLUTION WAS FOUND.
115   IF (ISW.EQ.0) WRITE (6,137)
      ISW=2
      TINCR=TINCR*.5
      THETAB=THETAB-TINCR
      IF (ABS(TINCR)-TOL) 118,107,107
116   TINCR=TINCR*.5
      THETAB=THETAB+TINCR
      IF (ABS(TINCR)-TOL) 118,107,107
117   THETAI=THETAI-TINCR
      TINCR=TINCR/2.
      IF (ABS(TINCR)-TOL) 118,120,120
C     ITERATION COMPLETE. DO CALCULATIONS FOR LARGEST THETAI
118   ISW=-1
      GO TO 107
C     ITERATION ON THETAI IN PROCESS.
119   TINCR=TINCR/2.
      IF (ABS(TINCR)-TOL) 118,120,120
120   THETAI=THETAI+TINCR
      GO TO 107
C     THETAI TOO LARGE
121   GO TO 117
C     THETAB - THETAI TOO LARGE
122   GO TO 117
C     THETAB LESS THAN THETAI
123   WRITE (6,136)
      GO TO 114
C
124   FORMAT (//12H RATIOS ARE /)
125   FORMAT (//12X,14HRELATIVE ANGLE,10X,14HABSOLUTE ANGLE,/9X,5HTHETA,
     18X,4HBETA,7X,5HTHETA,8X,4HBETA,29H  UPSTREAM MACH     LOCAL MACH)
126   FORMAT (//7H REGION,10X,1HP,12X,3HRHO,11X,1HT,11X,1HA,11X,1HU,13X,
     12HMU,3X,11HREYNOLDS NO,9H  MACH NO)
127   FORMAT (14X,3HPSI,4X,10HSLUG/CU FT,5X,7HRANKINE,6X,6HFT/SEC,6X,6HF
     1T/SEC,4X,11HSLUG/FT-SEC,11X,4H1/FT)
128   FORMAT (1X,I5,F12.4,E15.5,3F12.4,2E15.5,F8.4)
```

```
129   FORMAT (/1X,25HSTAGNATION CONDITIONS ARE/7H REGION,6X,5HPSTAG,12X,
     13HRHO,7X,5HTSTAG,4X,12HPSTAG/PSTAG1,/,14X,4HPSIA,4X,11HSLUGS/CU FT
     2,5X,7HRANKINE)
130   FORMAT (//14H HEAT TRANSFER,/17X,1HQ,14X,3HHFP,12X,8HSTANTON4,7X,8
     1HSTANTON1,7X,5HP6/P4,10X,2HHR,12X,3HQPK,12X,3HHPK)
131   FORMAT (8H LAMINAR,2X,8(E15.5))
132   FORMAT (10H TURBULENT,8(E15.5))
133   FORMAT (1H1,50H THIS PROGRAM PERFORMS A TYPE 6 SHOCK INTERFERENCE,
     18H PATTERN//12H RUN NUMBER ,F5.2//)
134   FORMAT (1H1)
135   FORMAT (1H0,20HINPUT VARIABLES ARE /9H THETAI =,F9.4,19H DEG, AND
     1THETAB = ,F9.4,4H DEG//)
136   FORMAT (/28H THETAB IS LESS THAN THETAI )
137   FORMAT (/43H NO SOLUTION WAS FOUND FOR A TYPE 6 PATTERN)
138   FORMAT (1X,I1,4F12.4,2F15.4)
      END
C     ..................................................................
```

Subroutine EXPNS

Subroutine EXPNS calculates the Mach number across an expansion layer by using an iterative procedure. The flow diagram and listing follow.

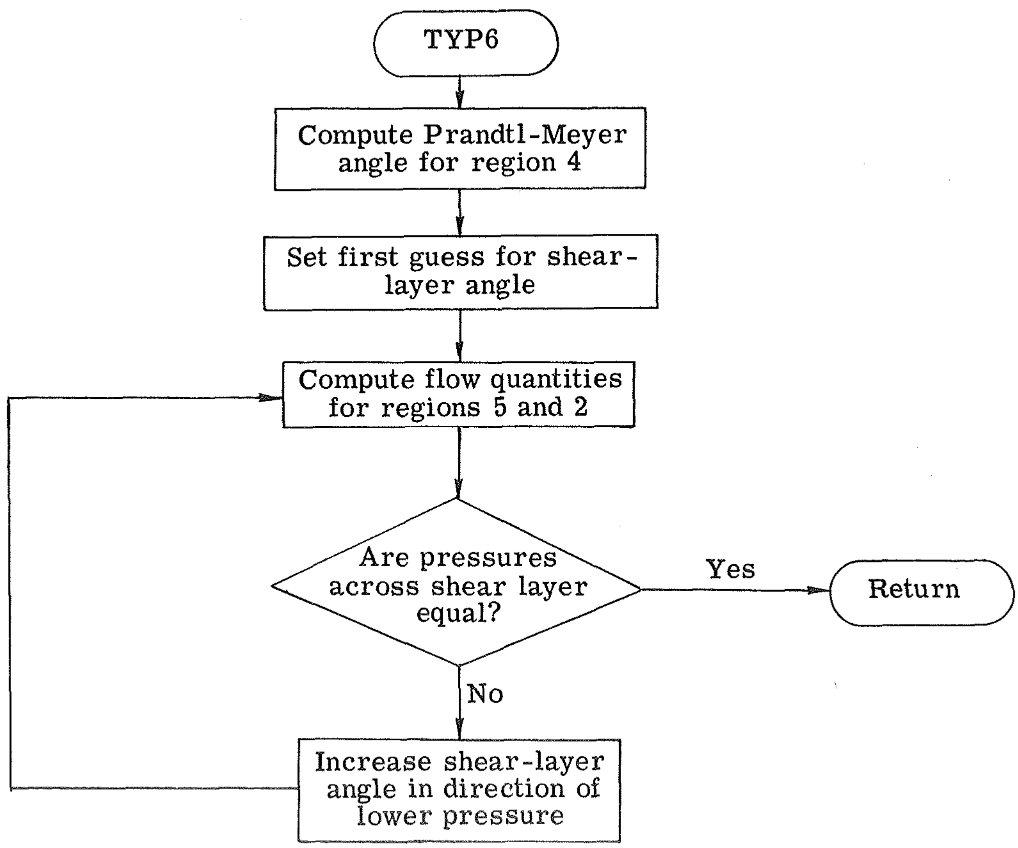



```
      SUBROUTINE EXPNS (RNU,RM,GAMMA,IERROR)
C
C     PURPOSE
C     FIND MACH NUMBER ACROSS EXPANSION LAYER KNOWING NU AND GAMMA.
C     RM SHOULD ORIGINALLY HOLD INITIAL GUESS.
C     F(M) = A * ATAN(SQRT(B*(RM2-1.))) - ATAN(SQRT(RM2-1.)) - NU
C
      GP1=GAMMA+1.
      GM1=GAMMA-1.
C        CALCULATE THE 2 COEFFICIENTS IN F(M)
      A=SQRT(GP1/GM1)
      B=GM1/GP1
      IERROR=0
      IT=0
      TOL=.0001
C        CALCULATE NEW VALUE FOR RM
1     CONTINUE
      RM2M1=RM*RM-1.
      DFM=A*B*RM/(SQRT(B*RM2M1)*(1.+B*RM2M1))-1./(RM*SQRT(RM2M1))
      FM=A*ATAN(SQRT(B*RM2M1))-ATAN(SQRT(RM2M1))-RNU
      RM1=RM-FM           /DFM
C       HAS RM CONVERGED
      IF (ABS(RM1-RM)-TOL) 3,3,2
C       CONTINUE ITERATING
```

```
2       RM=RM1
        IT=IT+1
        IF (IT.GT.50) GO TO 4
        IF (RM.LE.1.) GO TO 5
        GO TO 1
C         ITERATION IS COMPLETE
3       RM=RM1
        RETURN
C         HAS EXCEEDED NUMBER OF ITERATIONS ALLOWED
4       IERROR=1
        RETURN
C         THE MACH NUMBER HAS FALLEN BELOW THE LOWER LIMIT OF 1.
5       IERROR=2
        RETURN
        END
C       ..................................................................
```

Subroutine TYP6

Subroutine TYP6 calculates the shear-layer angle for a type VI flow interference pattern. The flow diagram and listing follow.



```
      SUBROUTINE TYP6 (THETAF,BETA2,RM1,RM4,RM5,THETAB,P1,P4,P5,GAMMA,TO
     1L,IERROR,OPTION,P2OP1)
C     PURPOSE
C     CALCULATE THETAF FOR A TYPE 6 SHOCK INTERFERENCE PATTERN
C     DESCRIPTION OF VARIABLES
C     THETAF = DEFLECTION ANGLE FOR POINT 2 IN RADIANS, OUTPUT
C     BETA2  = SHOCK(WEAK) ANGLE FOR POINT 2 IN RADIANS, OUTPUT
C     RM1    = INITIAL MACH NUMBER, INPUT
C     RM4    = MACH NUMBER AT POINT 4, INPUT
C     RM5    = MACH NUMBER AT POINT 5, OUTPUT
C     THETAB = ANGLE OF SECOND SHOCK DEFLECTION. USED AS INITIAL
C              ESTIMATE FOR THETAF
C     P1     = ABSOLUTE PRESSURE AT POINT 1, INPUT
C     P4     = ABSOLUTE PRESSURE AT POINT 4, INPUT
C     P5     = ABSOLUTE PRESSURE AT POINT 5, OUTPUT
C     GAMMA  = CP/CV
C     TOL    = CONVERGENCE CRITERIA FOR THETAF
C     IERROR = 0  NO ERROR
C              1  EXCEEDED ALLOWABLE NUMBER OF ITERATIONS
C              2  NO SOLUTION FOUND FOR THETAF
      DATA OPT/4HAXIS/
C     ISENTROPIC PRESSURE RATIO ( P STAGNATION / P )
      PZOP(GAMMA,GM1,RM)=(1.+GM1*RM*RM/2.)**(GAMMA/GM1)
C     FOR EXTRA PRINTOUT SET DEBUG TO 1.
      DEBUG=0.
      RM42M1=RM4*RM4-1.
      GP1=GAMMA+1.
      GM1=GAMMA-1.
C              CALCULATE COEFFICIENTS FOR EQ OF NU
      A=SQRT(GP1/GM1)
      B=GM1/GP1
C              CALCULATE NU4
      RNU4=A*ATAN(SQRT(B*RM42M1))-ATAN(SQRT(RM42M1))
      IERROR=0
      IT=0
C              SET INITIAL ESTIMATE FOR RM5
      RM5=RM4
C              SET INITIAL ESTIMATE FOR THETAF
      THETAF=THETAB
C     THETAF INCREMENT
      DTHETA=.1
      ISW=0
C     FIND WEAK SHOCK ANGLE FOR 2
1     IERR=1
      BETA2=FINDB(GAMMA,RM1,ABS(THETAF),1,IERR)
C     WAS A SOLUTION FOUND
      IF (IERR.GT.2) GO TO 8
C     FIND PRESSURE AT PT 2
      SINB2=SIN(BETA2)
      P2OP1=PRATIO(GAMMA,RM1,SINB2)
      ISW=1
      P2=P2OP1*P1
C      FIND PRESSURE AT PT 5
      RNU5=RNU4+ABS(THETAF-THETAB)
      CALL EXPNS (RNU5,RM5,GAMMA,IERR)
      IF (IERR.GT.0) GO TO 10
C     STAGNATION PRESSURE AT 4
      PZOP4=PZOP(GAMMA,GM1,RM4)
      P40=PZOP4*P4
      PZOP5=PZOP(GAMMA,GM1,RM5)
```

```
C         P50 IS SAME AS P40
        P5=P40/P2OP5
C       INTERATION COMPLETE
        IF (DEBUG.GT.0) WRITE (6,11) THETAF,P2,P5,RNU4,RNU5,RM5
        IF (ABS(P5-P2).LT.TCL) RETURN
C       CONTINUE ITERATING
        IF (IT.GT.50) GO TO 7
        IT=IT+1
        IF (P5.GT.P2) GO TO 4
C        P2.GT.P5 - DECREASE THETAF
        THETAF=THETAF-DTHETA
        IF (ISW) 1,3,2
2       DTHETA=DTHETA/2.
        THETAF=THETAF+DTHETA
        GO TO 1
3       ISW=-1
        GO TO 1
C        P5.GT.P2 - INCREASE THETAF
4       THETAF=THETAF+DTHETA
        IF (ISW) 5,6,1
5       DTHETA=DTHETA/2.
        THETAF=THETAF-DTHETA
        GO TO 1
6       ISW=1
        GO TO 1
C       HAS EXCEEDED ALLOWABLE NUMBER OF ITERATIONS
7       IERROR=1
        RETURN
C       NO SOLUTION WAS FOUND FOR BETA2. THETAF IS TOO LARGE. IF ISW IS
C       0 - THEN ORIGINAL ESTIMATE FOR THETAF WAS TOO LARGE
8       THETAF=THETAF-DTHETA
        IF (ISW) 1,1,9
9       DTHETA=DTHETA/2.
        IF (DTHETA.GT.0.0001) GO TO 1
C       A TYPE 6 INTERFERENCE PATTERN WAS NOT POSSIBLE. HAS DEGENERATED
C       TO A TYPE 5
        IERROR=2
        RETURN
10      WRITE (6,12) IERR,RNU4,RM4,RNU5,RM5
        CALL EXIT
C
11      FORMAT (10F12.5)
12      FORMAT (I5,4F12.5,5X,24HNO SOLUTION FOUND FOR M5)
        END
C       ..................................................................
```

USAGE

Program SHOCK for a type VI interference pattern uses the standard FORTRAN NAMELIST input with $DATAIN as the NAMELIST name. The input includes the flow conditions, gas properties, flow deflection or shock angle, impingement location on the body, and body angle. The program can increment the shock generator angle and also predict when a type V interference pattern will occur.

A description of the input and output variables and a sample case are presented.

Input Description

The $DATAIN input for type VI is as follows:

RUN	run number for identification
RM1	M_∞, free-stream Mach number
GAMMA	c_p/c_v, ratio of specific heats
THETAI	θ_i, shock-generator angle, deg; or β_i, impinging shock angle, deg
THETAB	θ_b, body angle, deg; or β_b, bow shock angle, deg
TINCR	increment for θ_i, deg (Default = 5^o)
NTIMES	number of times to increment θ_i
IPT	initial point; 0 for stagnation conditions, 1 for free-stream static conditions
T	temperature at IPT, ^{o}R
P	pressure at IPT, psia
AMW	molecular weight (used to compute gas constant)
TREF	reference temperature for computing viscosity, ^{o}R
VREF	reference viscosity for computing viscosity, slugs/ft-sec
S	Sutherland's constant in viscosity equation
XL	X_i, distance from leading edge to impingement point, ft
TWALL	temperature at wall, ^{o}R
CP	c_p, specific heat at constant pressure, ft-lbf/slug-^{o}R

PR	N_{Pr}, Prandtl number
ANGLE	THET if θ_i input; BETA if β_i input
ANGLE2	THET if θ_b input; BETA if β_b input
TOL	acceptable tolerance for equal pressures (0.001)

Output Description

The output consists of printing only. A heading and pertinent input for identification are printed before the results of the calculations.

RUN NUMBER	run number for identification
M1	M_∞, Mach number in free stream
GAMMA (CP/CV)	ratio of specific heats
TEMP AT POINT "IPT"	input as T, ^oR
PRES AT POINT "IPT"	input as P, psia
MOLECULAR WEIGHT	molecular weight (used to compute gas constant)
REFERENCE TEMP	reference temperature for computing viscosity, ^oR
REFERENCE VISCOSITY	reference viscosity for computing viscosity, slugs/ft-sec
S(SUTHERLAND NUMBER)	Sutherland's constant in viscosity equation
TEMP AT WALL	T_w, ^oR
CP	c_p, specific heat at constant pressure, ft-lbf/slug-^oR
PRANDTL NUMBER	N_{Pr}, Prandtl number
XL(WALL LENGTH)	X_i, length from leading edge to impingement point, ft
THETAI	θ_i, shock generator angle, deg

THETAB	θ_b, body angle, deg
P2/P1, etc.	p_2/p_1, etc., pressure ratios for regions listed
RHO2/1, etc.	ρ_2/ρ_1, etc., density ratios for regions listed
T2/T1, etc.	T_2/T_1, etc., temperature ratios for regions listed
A2/A1, etc.	a_2/a_1, etc., ratios of speeds of sound in regions listed
U2/U1, etc.	u_2/u_1, etc., velocity ratios for regions listed
RELATIVE ANGLE	
THETA	flow angle relative to flow in upstream region, deg
BETA	shock angle relative to flow in upstream region, deg
ABSOLUTE ANGLE	
THETA	flow angle relative to free-stream flow, deg
BETA	shock angle relative to free-stream flow, deg
UPSTREAM MACH	Mach number in upstream region
LOCAL MACH	local Mach number
REGION	region in shock pattern
P	static pressure in region, psia
RHO	static density in region, slugs/ft^3
T	static temperature in region, $^{\circ}$R
A	speed of sound in region, ft/sec
U	velocity in region, ft/sec

MU	static viscosity in region, slugs/ft-sec
REYNOLDS NO	Reynolds number per foot in region
MACH NO	Mach number in region

The following stagnation conditions are then listed:

PSTAG	total pressure in region, psia
RHO	total density in region, slugs/ft^3
TSTAG	total temperature in region, $^{\circ}$R
PSTAG/PSTAG1	ratio of total pressure in region to free-stream total pressure

The pressure ratio and heat transfer for laminar and turbulent flow are listed as

Q	heat-transfer rate, Btu/ft^2-sec
HFP	flat-plate heat-transfer coefficient, Btu/ft^2-sec-$^{\circ}$R
STANTON4	local incompressible Stanton number
STANTON1	compressible free-stream Stanton number
P6/P4	pressure ratio
HR	Markarian heat-transfer ratio
QPK	peak heating rate
HPK	peak heat-transfer coefficient

Sample Case – Input

```
$DATAIN
RM1     =  0.6E+01,
GAMMA   =  0.14E+01,
THETAB  =  0.15E+02,
THETAI  =  0.5E+01,
TINCR   =  0.5E+01,
NTIMES  =  1,
IPT     =  0,
T       =  0.9E+03,
P       =  0.4E+03,
AMW     =  0.2897E+02,
TREF    =  0.53E+03,
VREF    =  0.3801E-06,
XL      =  0.25E+00,
S       =  0.1986E+03,
TWALL   =  0.55E+03,
CP      =  0.6006E+04,
PR      =  0.72E+00,
RUN     =  0.1E+01,
ANGLE   =  0.69404725765109E+93,
ANGLE2  =  0.69404725765109E+93,
TOL     =  0.1E-02,
$END
```

Sample Case – Output

```
THIS PROGRAM PERFORMS A TYPE 6 SHOCK INTERFERENCE PATTERN
RUN NUMBER  1.00


INPUT VARIABLES ARE

M1                                   6.000
GAMMA(CP/CV)                         1.400000
TEMP AT POINT 0                    900.000000   RANKINE
PRES AT POINT 0                    400.000000   PSI
MOLECULAR WEIGHT                    28.970000
REFERENCE TEMP                     530.000000   RANKINE
REFERENCE VISCOSITY               3.801000E-07  SLUG/(FT-SEC)
S(SUTHERLAND NUMBER)               198.600
TEMP AT WALL                       550.000      RANKINE
CP                                6006.000      FT-LBF/(SLUG-RANKINE)
PRANDTL NUMBER                      .720000
XL(WALL LENGTH)                     .250000     FT
```

INPUT VARIABLES ARE
THETAI = 5.0000 DEG, AND THETAB = 15.0000 DEG

RATIOS ARE

P2/P1=	6.2657	RHO2/1=	3.1465	T2/T1=	1.9913	A2/A1=	1.4111	U2/U1=	.9286
P3/P1=	2.0103	RHO3/1=	1.6306	T3/T1=	1.2328	A3/A1=	1.1103	U3/U1=	.9837
P4/P3=	3.2313	RHO4/3=	2.2085	T4/T3=	1.4631	A4/A3=	1.2096	U4/U3=	.9582
P4/P1=	6.4957	RHO4/1=	3.6013	T4/T1=	1.8037	A4/A1=	1.3430	U4/U1=	.9425

	RELATIVE ANGLE		ABSOLUTE ANGLE			
	THETA	BETA	THETA	BETA	UPSTREAM MACH	LOCAL MACH
2	15.3412	23.0383	15.3413	23.0383	6.0000	3.9483
3	5.0000	13.1598	5.0000	13.1598	6.0000	5.3157
4	10.0000	18.7264	15.0000	23.7264	5.3157	4.2108
5	5.3413	18.7264	15.3413	23.7264	4.2108	4.2388

REGION	P	RHO	T	A	U	MU	REYNOLDS NO	MACH NO
	PSI	SLUG/CU FT	RANKINE	FT/SEC	FT/SEC	SLUG/FT-SEC	1/FT	
1	.2533	1.93645E-04	109.7561	513.5679	3081.4074	8.46377E-08	7.05004E+06	6.0000
2	1.5874	6.09309E-04	218.5598	724.7174	2861.4275	1.75803E-07	9.91731E+06	3.9483
3	.5093	3.15760E-04	135.3111	570.2302	3031.1919	1.06990E-07	8.94597E+06	5.3157
4	1.6457	6.97365E-04	197.9706	689.7376	2904.3537	1.59424E-07	1.27045E+07	4.2108
5	1.5870	6.79541E-04	195.9276	686.1694	2908.5544	1.57775E-07	1.25272E+07	4.2388

STAGNATION CONDITIONS ARE

REGION	PSTAG	RHO	TSTAG	PSTAG/PSTAG1
	PSIA	SLUGS/CU FT	RANKINE	
1	400.0000	3.72856E-02	900.0000	
2	224.9256	2.09662E-02	900.0010	.5623
3	386.5123	3.60280E-02	900.0088	.9663
4	329.6872	3.07311E-02	900.0107	.8242
5	329.6872	3.07314E-02	900.0000	.8242

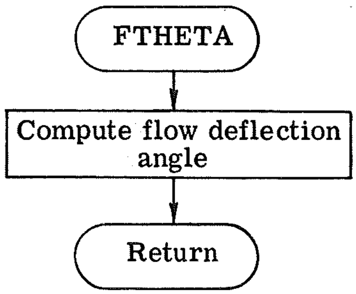
HEAT TRANSFER

	Q	HFP	STANTON4	STANTON1	P6/P4	HR	QPK	HPK
LAMINAR	8.37207E-01	3.43593E-03	5.66997E-04	7.45904E-04	9.28770E-01	9.09079E-01	7.61087E-01	3.12353E-03
TURBULENT	4.25952E+00	1.53670E-02	2.53586E-03	3.33601E-03	9.28770E-01	9.39122E-01	4.00021E+00	1.44315E-02

A description of each of the subprograms common to more than one main program is presented along with a flow chart and listing.

FTHETA

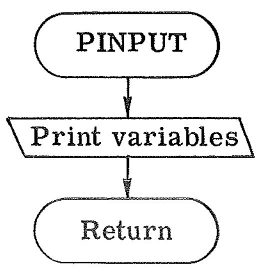
Function FTHETA computes the flow deflection angle given the Mach number ahead of the shock, the ratio of specific heats, and the shock angle. The flow diagram and listing are as follows:




```
      FUNCTION FTHETA (GAMMA,RM,BETA)                                   B   3
C     FIND FLOW ANGLE                                                   B   4
      SINB=SIN(BETA)                                                    B   5
      SINBSQ=SINB*SINB                                                  B   6
      COS2B=COS(2.*BETA)                                                B   7
      RMSQ=RM*RM                                                        B   8
      RMSB2=RMSQ*SINBSQ                                                 B   9
      TANB=TAN(BETA)                                                    B  10
      TANTH=2.*(RMSB2-1.)/(TANB*(RMSQ*(GAMMA+COS2B)+2.))                B  11
      FTHETA=ATAN(TANTH)                                                B  12
      RETURN                                                            B  13
      END                                                               B  14-
C     ..................................................................A   1
```

PINPUT

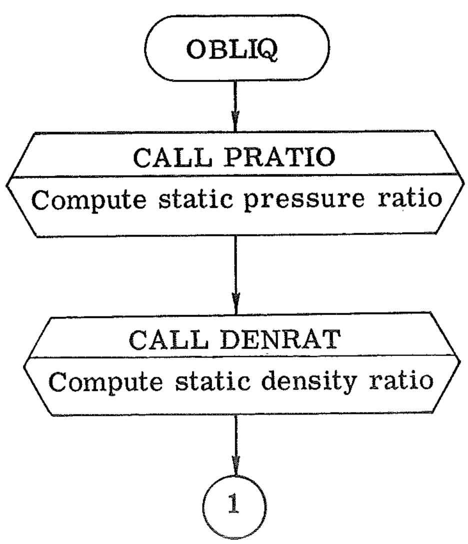
Subroutine PINPUT prints out the input variables. The flow diagram and listing for this subroutine are as follows:

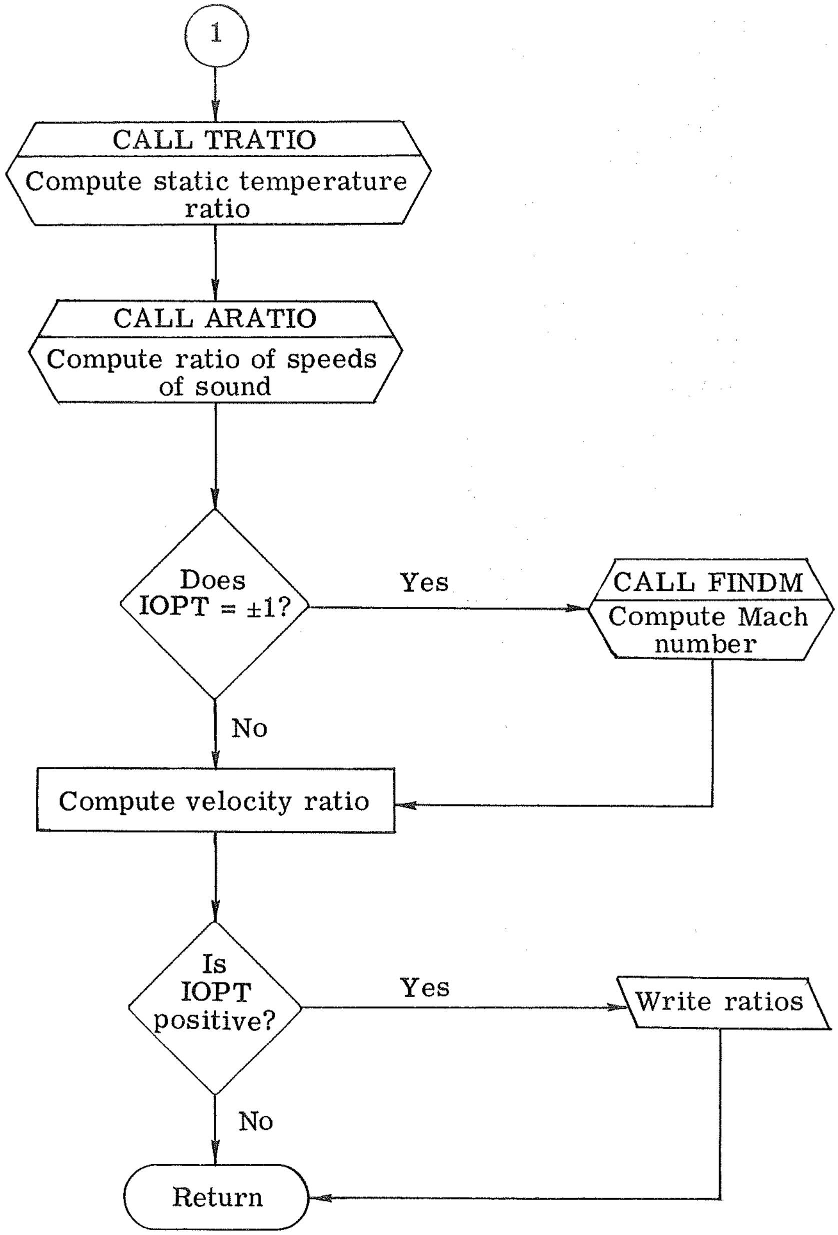


```
      SUBROUTINE PINPUT (RM1,GAMMA,IPT,T,P,AMW,TREF,VREF,XL,S,TWALL,CP,P
     1R)
C     PRINT OUT INPUT VARIABLES
      WRITE (6,1)
      WRITE (6,11) RM1
      WRITE (6,12) GAMMA
      WRITE (6,2) IPT,T
      WRITE (6,3) IPT,P
      WRITE (6,4) AMW
      WRITE (6,5) TREF
      WRITE (6,6) VREF
      WRITE (6,7) S
      WRITE (6,8) TWALL
      WRITE (6,9) CP
      WRITE (6,10) PR
      RETURN
C
1     FORMAT (1H0,20HINPUT VARIABLES ARE /)
2     FORMAT (14H TEMP AT POINT,I2,15X,F15.6,9H  RANKINE)
3     FORMAT (14H PRES AT POINT,I2,15X,F15.6,6H  PSI )
4     FORMAT (17H MOLECULAR WEIGHT,14X,F15.6)
5     FORMAT (15H REFERENCE TEMP,16X,F15.6,9H  RANKINE)
6     FORMAT (20H REFERENCE VISCOSITY,11X,E15.6,15H  SLUG/(FT-SEC))
7     FORMAT (21H S(SUTHERLAND NUMBER),10X,F15.3)
8     FORMAT (13H TEMP AT WALL,18X,F15.3,9H  RANKINE)
9     FORMAT (3H CP,28X,F15.3,23H  FT-LBF/(SLUG-RANKINE))
10    FORMAT (15H PRANDTL NUMBER,16X,F15.6)
11    FORMAT (3H M1,28X,F15.3)
12    FORMAT (13H GAMMA(CP/CV),18X,F15.6)
      END
```

OBLIQ

Subroutine OBLIQ calculates the flow-property ratios across an oblique shock. The flow diagram and listing are as follows:





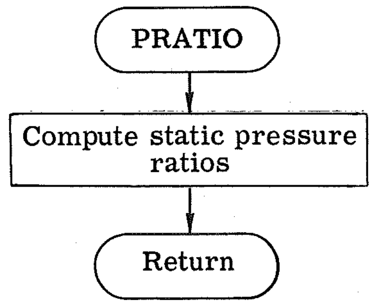

```
      SUBROUTINE OBLIQ (GAMMA,RMI,THETAJ,BETAJ,RMJ,RAT,I,J,IOPT)
C     ..................................................................
C     PURPOSE
C        TO CALCULATE THE OBLIQUE SHOCK RELATIONS FOR PRESSURE, DENSITY,
C        TEMPERATURE, SONIC VELOCITY, VELOCITY, AND MACH NUMBER FOR
C        CONDITIONS I BEFORE THE SHOCK AND J AFTER THE SHOCK
C
C     USAGE
C
C        OBLIQ(GAMMA, RMI, THETAJ, BETAJ, RMJ, RAT, I, J, IOPT )
C
```

```
C       DESCRIPTION OF VARIABLES
C          GAMMA = RATIO OF SPECIFIC HEAT CAPACITIES(CP/CV)
C          RMI   = MACH NUMBER BEFORE THE SHOCK
C          THETAJ= DEFLECTICN ANGLE OF THE STREAMLINES IN RADIANS
C          BETAJ = SHOCK ANGLE IN RADIANS
C          RMJ   = MACH NUMBER AFTER THE SHOCK
C          RAT(1)= PJOPI   DOWNSTREAM PRESSURE OVER UPSTREAM PRESSURE
C          RAT(2)= RHOJOI  DOWNSTREAM DENSITY OVER UPSTREAM DENSITY
C          RAT(3)= TJOTI   DOWNSTREAM TEMPERATURE OVER UPSTREAM TEMP
C          RAT(4)= AJCAI   DOWNSTREAM SONIC VELOCITY OVER   UPSTREAM SOMIC
C          RAT(5)= UJOUI   DOWNSTREAM VELOCITY OVER   UPSTREAM VELOCITY
C          I     = UPSTREAM CCNDITIONS
C          J     = DOWNSTREAM CONDITIONS
C          IOPT  = 1,-1 CALCULATE RMJ
C                  2,-2 DO NOT CALCULATE RMJ
C                  POSITIVE  PRINT RATIOS
C                  NEGATIVE  DO NOT PRINT RATIOS
C
C       ...........................................................
        COMMON  PZ, RHOZ, TZ, P1OPZ, RHO1OZ, T1OTZ,
      1         PZ2, RHOZ2, TZ2, P2OPZ2, RHO2Z2, T2OTZ2,
      2         PZ3, RHOZ3, TZ3, P3OPZ3, RHO3Z3, T3OTZ3,
      3         PZ4, RHOZ4, TZ4, P4OPZ4, RHO4Z4, T4OTZ4,
      4         PZ5, RHOZ5, TZ5, P5OPZ5, RHO5Z5, T5OTZ5,
      5         PZ6, RHOZ6, TZ6, P6OPZ6, RHO6Z6, T6OTZ6,
      6         P2OP1, RHO2O1, T2OT1, A2OA1, U2OU1,
      7         P3OP2, RHO3O2, T3OT2, A3OA2, U3OU2,
      8         P3OP1, RHO3C1, T3OT1, A3OA1, U3OU1,
      9         P4OP2, RHO4O2, T4OT2, A4OA2, U4OU2,
      $         P4OP1, RHO4O1, T4OT1, A4OA1, U4OU1,
      $         P5OP3, RHO5C3, T5OT3, A5OA3, U5OU3,
      $         P6OP5, RHO6C5, T6OT5, A6OA5, U6OU5,
      $         P5OP1, RHO5O1, T5OT1, A5OA1, U5OU1,
      $         P6OP1, RHO6C1, T6OT1, A6OA1, U6OU1
        COMMON  P6OP3, RHO6C3, T6OT3, A6OA3, U6OU3
        CCMMCN  P1, RHO1, T1, A1, U1, VISC1, REY1,
      1         P2, RHO2, T2, A2, U2, VISC2, REY2,
      2         P3, RHO3, T3, A3, U3, VISC3, REY3,
      3         P4, RHO4, T4, A4, U4, VISC4, REY4,
      4         P5, RHO5, T5, A5, U5, VISC5, REY5,
      5         P6, RHO6, T6, A6, U6, VISC6, REY6
        DIMENSION RAT(5)
C                                FIND RATIOS USING OBLIQUE SHOCK RELATIONS
        SINB=SIN(BETAJ)
C                                CALCULATE PRESSURE RATIOS
        PJOPI=PRATIO(GAMMA,RMI,SINB)
C                                CALCULATE DENSITY RATIOS
        RHOJOI=DENRAT(GAMMA,RMI,SINB)
C                                CALCULATE TEMPERATURE RATIOS
        TJOTI=TRATIO(GAMMA,RMI,SINB)
C                                CALCULATE SOMIC VELOCITY RATIO
        AJOAI=ARATIO(TJOTI)
C                                CALCULATE MACH NUMBER AT CONDITION J
        IF (IABS(IOPT)-1) 2,1,2
1       RMJ=FINDM(GAMMA,RMI,SINB,BETAJ,THETAJ)
C                                CALCULATE VELOCITY RATIO
2       UJOUI=AJOAI*RMJ/RMI
        RAT(1)=PJOPI
        RAT(2)=RHCJOI
        RAT(3)=TJOTI
        RAT(4)=AJOAI
        RAT(5)=UJOUI
```

```
C                        IF IOPT POSITIVE WRITE RATIOS
      IF (IOPT) 4,3,3
3     CONTINUE
      WRITE (6,5) J,I,PJOPI,J,I,RHOJOI,J,I,TJOTI,J,I,AJOAI,J,I,UJOUI
4     RETURN
C
5     FORMAT (1X,1HP,I1,2H/P,I1,1H=,F8.4,5X,3HRHO,I1,1H/,I1,1H=,F8.4,5X,
     11HT,I1,2H/T,I1,1H=,F8.4,5X,1HA,I1,2H/A,I1,1H=,F8.4,5X,1HU,I1,2H/U,
     2I1,1H=,F8.4)
      END
```

PRATIO

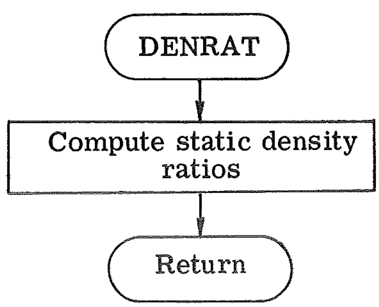
Function PRATIO computes the ratios of the static pressures across an oblique shock. The flow diagram and listing are as follows:




```
      FUNCTION PRATIO (GAMMA,RM,SINB)
C     FIND RATIOS OF STATIC PRESSURES,  SINB=SIN(BETA)
      PRATIO=2*GAMMA*(RM**2*SINB**2-1.)/(GAMMA+1.)+1.0
      RETURN
      END
C     ..........................................................
```

DENRAT

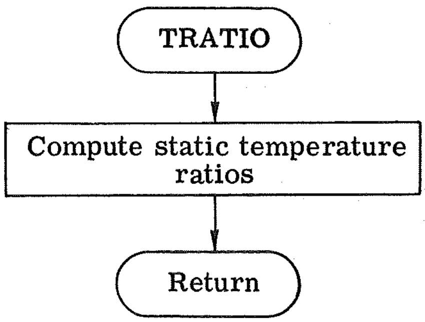
Function DENRAT computes the ratios of the static densities across an oblique shock. The flow diagram and listing of this function are as follows:



```
      FUNCTION DENRAT (GAMMA,RM,SINB)
C     FIND RATIOS OF STATIC DENSITIES,   SINB=SIN(BETA)
      RMSQ=RM*RM
      SINBSQ=SINB*SINB
      DENRAT=(GAMMA+1.)*RMSQ*SINBSQ/((GAMMA-1.)*RMSQ*SINBSQ+2.)
      RETURN
      END
C     ......................................................................
```

TRATIO

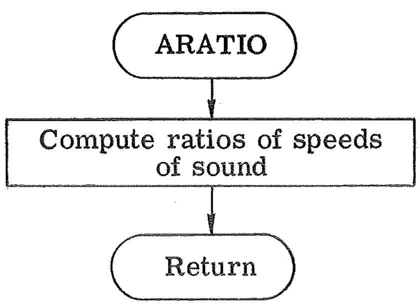
Function TRATIO computes the ratios of the static temperatures across an oblique shock. The flow diagram and listing are as follows:




```
      FUNCTION TRATIO (GAMMA,RM,SINB)
C     FIND RATIOS OF STATIC TEMPERATURES,   SINB=SIN(BETA)
      SINBSQ=SINB*SINB
      RMSQ=RM*RM
      RMSB2=RMSQ*SINBSQ
      GAMMAR=2*(GAMMA-1.)/(GAMMA+1.)**2
      TRATIO=1.+GAMMAR*(RMSB2-1.)*(GAMMA*RMSB2+1.)/RMSB2
      RETURN
      END
C     ......................................................................
```

ARATIO

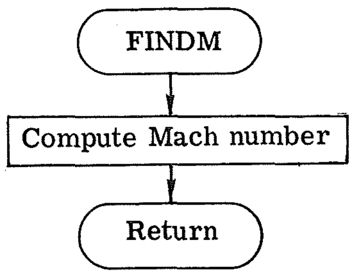
Function ARATIO computes the ratios of the speeds of sound across an oblique shock. The flow diagram and listing are as follows:



```
      FUNCTION ARATIO (T2OT1)
C     FIND RATIOS OF SPEEDS OF SOUND
      ARATIO=SQRT(T2OT1)
      RETURN
      END
C     ...............................................................
```

FINDM

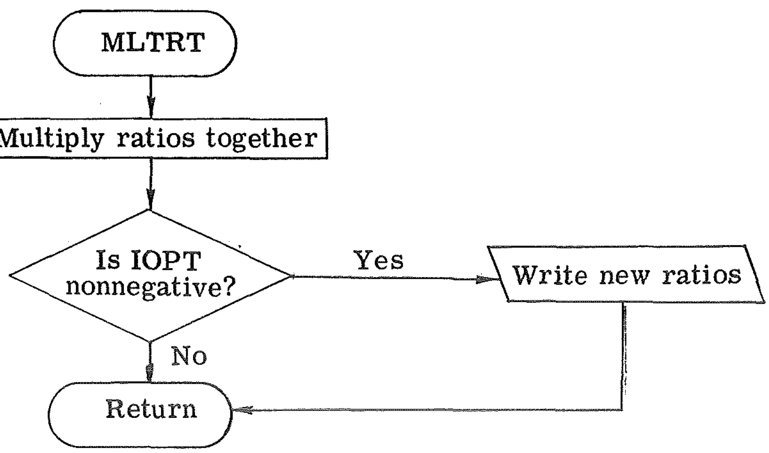
Function FINDM computes the Mach number behind an oblique shock. The flow diagram and listing are as follows:




```
      FUNCTION FINDM (GAMMA,RM1,SINB,BETA,THETA)
C     FIND MACH NUMBER, SINB=SIN(BETA)
      SINBSQ=SINB*SINB
      RMSQ=RM1*RM1
      RMSB2=RMSQ*SINBSQ
      C=(1.+(GAMMA-1.)*RMSB2/2.)/(GAMMA*RMSB2-(GAMMA-1.)/2.)
      FINDM=SQRT(C)/ABS(SIN(BETA-THETA))
      RETURN
      END
C     ...............................................................
```

MLTRT

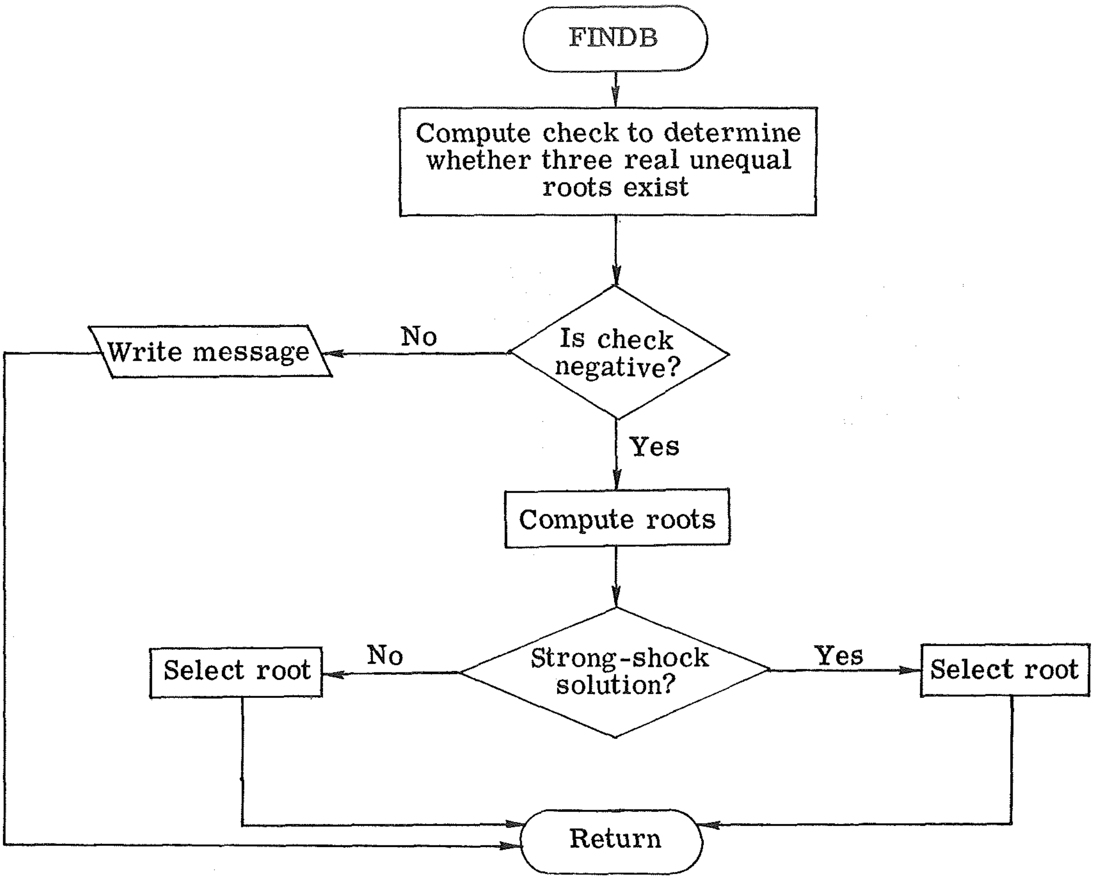
Subroutine MLTRT computes the ratios of the flow quantities in each region with respect to the free-stream values by multiplying the ratios across oblique shocks. The subroutine flow diagram and listing are as follows:



```
      SUBROUTINE MLTRT (RATIOJ,RATIOI,RATJOI,I,J,IOPT)
C     MULTIPLY RATIOS TO OBTAIN RATIOS WITH RESPECT TO FREE STREAM
      DIMENSION RATIOJ(5), RATIOI(5), RATJOI(5)
      COMMON  PZ, RHOZ, TZ, P1OPZ, RHO1OZ, T1OTZ,
     1        PZ2, RHOZ2, TZ2, P2OPZ2, RHO2Z2, T2OTZ2,
     2        PZ3, RHOZ3, TZ3, P3OPZ3, RHO3Z3, T3OTZ3,
     3        PZ4, RHOZ4, TZ4, P4OPZ4, RHO4Z4, T4OTZ4,
     4        PZ5, RHOZ5, TZ5, P5OPZ5, RHO5Z5, T5OTZ5,
     5        PZ6, RHOZ6, TZ6, P6OPZ6, RHO6Z6, T6OTZ6,
     6        P2OP1, RHO2O1, T2OT1, A2OA1, U2OU1,
     7        P3OP2, RHO3O2, T3OT2, A3OA2, U3OU2,
     8        P3OP1, RHO3O1, T3OT1, A3OA1, U3OU1,
     9        P4OP2, RHO4O2, T4OT2, A4OA2, U4OU2,
     $        P4OP1, RHO4O1, T4OT1, A4OA1, U4OU1,
     $        P5OP3, RHO5O3, T5OT3, A5OA3, U5OU3,
     $        P6OP2, RHO6O2, T6OT2, A6OA2, U6OU2,
     $        P6OP4, RHO6O4, T6OT4, A6OA4, U6OU4,
     $        P5OP1, RHO5O1, T5OT1, A5OA1, U5OU1,
     $        P6OP1, RHO6O1, T6OT1, A6OA1, U6OU1
      COMMON  P1, RHO1, T1, A1, U1, VISC1, REY1,
     1        P2, RHO2, T2, A2, U2, VISC2, REY2,
     2        P3, RHO3, T3, A3, U3, VISC3, REY3,
     3        P4, RHO4, T4, A4, U4, VISC4, REY4,
     4        P5, RHO5, T5, A5, U5, VISC5, REY5,
     5        P6, RHO6, T6, A6, U6, VISC6, REY6
      DO 1 K=1,5
1     RATJOI(K)=RATIOJ(K)*RATIOI(K)
      IF (IOPT) 3,2,2
2     WRITE (6,4) (J,I,RATJOI(K),K=1,5)
3     RETURN
C
4     FORMAT (1X,1HP,I1,2H/P,I1,1H=,F8.4,5X,3HRHO,I1,1H/,I1,1H=,F8.4,5X,
     11HT,I1,2H/T,I1,1H=,F8.4,5X,1HA,I1,2H/A,I1,1H=,F8.4,5X,1HU,I1,2H/U,
     2I1,1H=,F8.4)
      END
```

FINDB

Function FINDB solves a cubic equation for the shock angle by using the upstream Mach number and the deflection angle. A code is provided which allows the user to specify a strong-shock solution or a weak-shock solution. The flow diagram and listing are as follows:

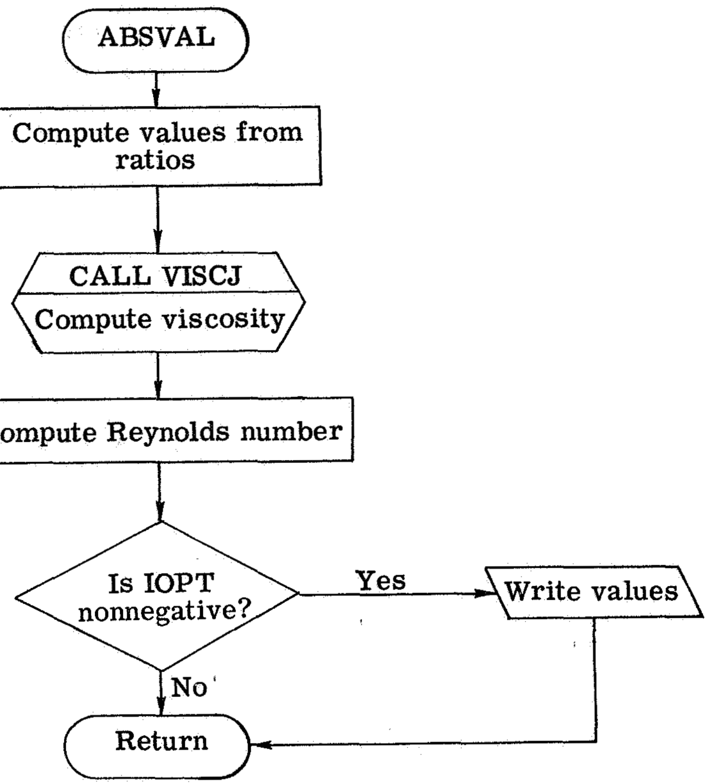



```
      FUNCTION FINDB (GAMMA,RM,THETA,IERROR)
C     PURPOSE
C     FIND SHOCK ANGLE
C
C     DESCRIPTION OF VARIABLES
C     GAMMA   CP/CV
C     RM      UPSTREAM MACH NUMBER
C     THETA   DEFLECTION ANGLE
C     ITYPE   2 FOR STRONG SHOCK SOLUTION AND 1 FOR WEAK SHOCK SOLUTION
C     IERROR  0 FOR NO ERROR
C             3 NO SOLUTION POSSIBLE
C
      DATA PI/3.1415927/
      DIMENSION BETA(3), ZZ(3), ZANS(3), TANANS(3)
      IPRINT=IERROR
      IERROR=0
      IF (ABS(THETA).LT..001) GO TO 4
      FMINIT=RM
      THETAC=THETA
      FMSQ=FMINIT*FMINIT
      SINTHE=SIN(THETAC)
      SINSQ=SINTHE*SINTHE
      PZ=-(FMSQ+2.0)/FMSQ-GAMMA*SINSQ
      GAMM1=GAMMA-1.0
      GAMP1=GAMMA+1.0
      GAMSQ=GAMP1*GAMP1
      FM4=FMSQ*FMSQ
```

```
      QZ=(2.0*FMSQ+1.0)/FM4+(GAMSQ/4.0+GAMM1/FMSQ)*SINSQ
      COSTHE=COS(THETAC)
      COSSQ=COSTHE*COSTHE
      RZ=-COSSQ/FM4
      PZSQ=PZ*PZ
      AZ=.3333333*(3.0*QZ-PZSQ)
      PZ3=PZ*PZSQ
      BZ=1.0/27.0*(2.0*PZ3-9.0*PZ*QZ+27.0*RZ)
      BZ2=BZ/2.0
      BZSQ=BZ2*BZ2
      AZ3=AZ/3.0
      AZCUB=AZ3*AZ3*AZ3
      ARGCK=BZSQ+AZCUB
      IF (ARGCK) 2,1,1
1     IERROR=3
      THDEG=THETA*57.296
      IF (IPRINT.LE.0) WRITE (6,6) GAMMA,RM,THDEG
      RETURN
2     COSPHI=-BZ2/SQRT(-AZCUB)
      PART=2.0*SQRT(-AZ3)
      PHI=ACOS(COSPHI)
      PHI3=PHI/3.0
      PZBY3=PZ/3.0
      ZZ(1)=PART*COS(PHI3)-PZBY3
      ZZ(2)=PART*COS(PHI3+.6666667*PI)-PZBY3
      ZZ(3)=PART*COS(PHI3+1.3333333*PI)-PZBY3
      DO 3 I=1,3
3     BETA(I)=ASIN(SQRT(ZZ(I)))
      TEMP1=AMAX1(BETA(1),BETA(2))
      TEMP2=AMAX1(BETA(2),BETA(3))
      TEMP3=AMAX1(BETA(1),BETA(3))
C     WEAK SHOCK
      FINCB=AMIN1(TEMP1,TEMP2,TEMP3)
      RETURN
4     IF (ITYPE.EQ.2) GO TO 5
      FINCB=ASIN(1./RM)
      RETURN
5     FINCB=1.5708
      RETURN
C
6     FORMAT (32H NO SOLUTION POSSIBLE FOR GAMMA=,F8.4,5H, RM=,F8.4,12H,
     1 AND THETA=,F8.4)
      END
```

ABSVAL

Subroutine ABSVAL calculates values of static pressure, static density, static temperature, speed of sound, velocity, static viscosity, and Reynolds number per foot for a region through the use of the ratios of values in that region with respect to free-stream values and the free-stream conditions. The flow diagram and listing are as follows:

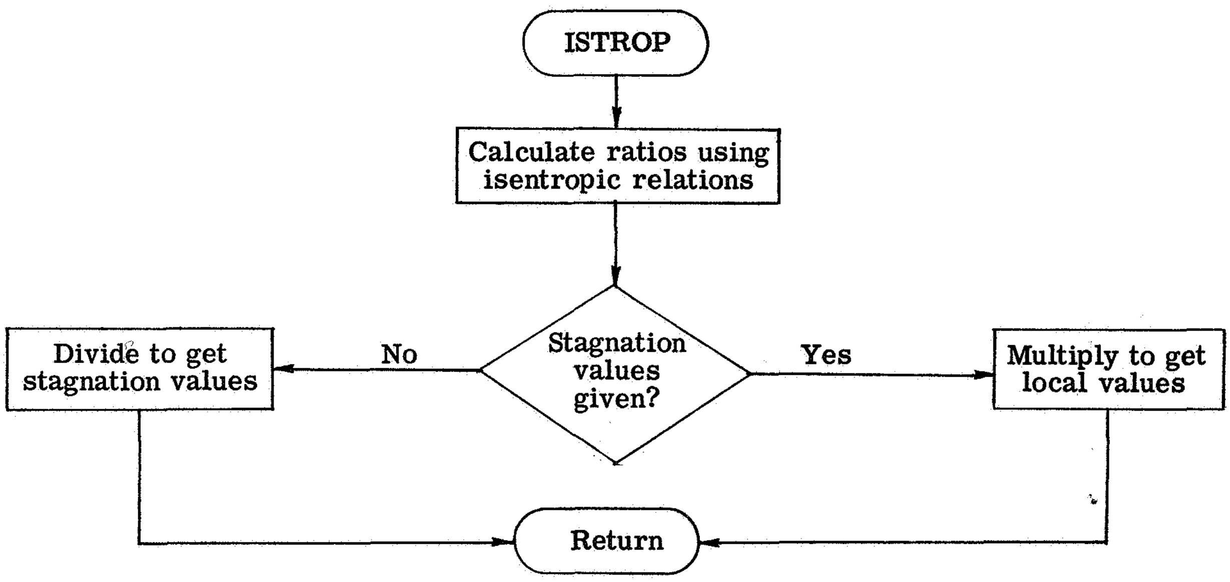



```
      SUBROUTINE ABSVAL (RAT,VALU1,VALUJ,VREF,TREF,S,J,IOPT,RMJ)
C     ..................................................................
C
C     PURPOSE
C     CALCULATE ABSOLUTE VALUES FOR PARAMETERS P, RHO, T, A, U, VISC,
C     AND REY FOR POINT J GIVEN VALUES AT POINT 1 AND THE RATIOS FOR
C     J OVER 1
C
C     ..................................................................
      COMMON  PZ, RHOZ, TZ, P1OPZ, RHO1OZ, T1OTZ,
     1        PZ2, RHOZ2, TZ2, P2OPZ2, RHO2Z2, T2OTZ2,
     2        PZ3, RHOZ3, TZ3, P3OPZ3, RHO3Z3, T3OTZ3,
     3        PZ4, RHOZ4, TZ4, P4OPZ4, RHO4Z4, T4OTZ4,
     4        PZ5, RHOZ5, TZ5, P5OPZ5, RHO5Z5, T5OTZ5,
     5        PZ6, RHOZ6, TZ6, P6OPZ6, RHO6Z6, T6OTZ6,
     6        P2OP1, RHO2O1, T2OT1, A2OA1, U2OU1,
     7        P3OP2, RHO3O2, T3OT2, A3OA2, U3OU2,
     8        P3OP1, RHO3O1, T3OT1, A3OA1, U3OU1,
     9        P4OP2, RHO4O2, T4OT2, A4OA2, U4OU2,
     $        P4OP1, RHO4O1, T4OT1, A4OA1, U4OU1,
     $        P5OP3, RHO5O3, T5OT3, A5OA3, U5OU3,
     $        P6OP5, RHO6O5, T6OT5, A6OA5, U6OU5,
     $        P5OP1, RHO5O1, T5OT1, A5OA1, U5OU1,
     $        P6OP1, RHO6O1, T6OT1, A6OA1, U6OU1
      COMMON  P6OP3, RHO6O3, T6OT3, A6OA3, U6OU3
      COMMON  P1, RHO1, T1, A1, U1, VISC1, REY1,
     1        P2, RHO2, T2, A2, U2, VISC2, REY2,
     2        P3, RHO3, T3, A3, U3, VISC3, REY3,
     3        P4, RHO4, T4, A4, U4, VISC4, REY4,
     4        P5, RHO5, T5, A5, U5, VISC5, REY5,
     5        P6, RHO6, T6, A6, U6, VISC6, REY6
```

```
      DIMENSION RAT(5), VALU1(7), VALUJ(7)
C                                CALCULATE P, RHO, T, A, AND U AT POINT J
      DO 1 I=1,5
1     VALUJ(I)=RAT(I)*VALU1(I)
C                                CALCULATE VISCOSITY
      VALUJ(6)=VISCJ(VREF,TREF,VALUJ(3),S)
C                                CALCULATE REYNOLDS NUMBER( RHO*U*XL/VISC )
      VALUJ(7)=VALUJ(2)*VALUJ(5)/VALUJ(6)
      IF (IOPT) 3,2,2
2     WRITE (6,4) J,(VALUJ(I),I=1,7),RMJ
3     RETURN
C
4     FORMAT (1X,I5,F12.4,E15.5,3F12.4,2E15.5,F8.4)
      END
```

ISTROP

Subroutine ISTROP calculates the static values or the total values of pressure, density, and temperature for a region with the use of isentropic relations. The flow diagram and listing are as follows:

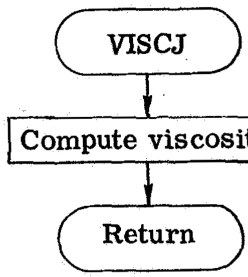



```
      SUBROUTINE ISTROP (GAMMA,RM1,VALU1,VALUZ,RATIO,IPT)
C     ..............................................................
C
C     PURPOSE
C        CALCULATE ISENTROPIC RELATIONS FOR P, RHO, T FROM STAGNATION
C        TO POINT 1 WITH M = RM1
C
C     DESCRIPTION OF VARIABLES
C        GAMMA
C        RM1
C        VALU1    VALUE OF P, T, RHO AT CONDITICN 1
```

```
C        VALUZ   VALUE OF P, T, RHO AT CONDITION ZERO
C        RATIC   RATIO OF P, T, RHO AT CONDITICN 1 OVER ZERO
C        IPT     0 OR 1, CONDITION WHICH WAS INPUT. CALCULATE THE OTHER.
C     ..............................................................
      DIMENSICN VALU1(7), VALUZ(3), RATIO(3)
      COMMCN  PZ, RHOZ, TZ, P1OPZ, RHO1OZ, T1OTZ,
     1        PZ2, RHOZ2, TZ2, P2OPZ2, RHO2Z2, T2OTZ2,
     2        PZ3, RHOZ3, TZ3, P3OPZ3, RHO3Z3, T3OTZ3,
     3        PZ4, RHOZ4, TZ4, P4OPZ4, RHO4Z4, T4OTZ4,
     4        PZ5, RHOZ5, TZ5, P5OPZ5, RHO5Z5, T5OTZ5,
     5        PZ6, RHOZ6, TZ6, P6OPZ6, RHO6Z6, T6OTZ6,
     6        P2OP1, RHO2O1, T2OT1, A2OA1, U2OU1,
     7        P3OP2, RHO3O2, T3OT2, A3OA2, U3OU2,
     8        P3OP1, RHO3O1, T3OT1, A3OA1, U3OU1,
     9        P4OP2, RHO4O2, T4OT2, A4OA2, U4OU2,
     $        P4OP1, RHO4O1, T4OT1, A4OA1, U4OU1,
     $        P5OP3, RHO5O3, T5OT3, A5OA3, U5OU3,
     $        P6OP2, RHO6O2, T6OT2, A6OA2, U6OU2,
     $        P6OP4, RHO6O4, T6OT4, A6OA4, U6OU4,
     $        P5OP1, RHO5O1, T5OT1, A5OA1, U5OU1,
     $        P6OP1, RHO6O1, T6OT1, A6OA1, U6OU1
      COMMCN  P1, RHO1, T1, A1, U1, VISC1, REY1,
     1        P2, RHO2, T2, A2, U2, VISC2, REY2,
     2        P3, RHO3, T3, A3, U3, VISC3, REY3,
     3        P4, RHO4, T4, A4, U4, VISC4, REY4,
     4        P5, RHO5, T5, A5, U5, VISC5, REY5,
     5        P6, RHO6, T6, A6, U6, VISC6, REY6
      C=(1.+(GAMMA-1.)*RM1**2/2.)
      P1OPZ=1./C**(GAMMA/(GAMMA-1.))
      RHC1OZ=1./C**(1./(GAMMA-1.))
      T1OTZ=1./C
      RATIO(1)=P1CPZ
      RATIO(2)=RHO1OZ
      RATIO(3)=T1OTZ
      IF (IPT) 3,3,1
1     DO 2 I=1,3
2     VALUZ(I)=VALU1(I)/RATIC(I)
      RETLRN
3     DO 4 I=1,3
4     VALU1(I)=VALUZ(I)*RATIC(I)
      RETURN
      END
C     ..............................................................
```

VISCJ

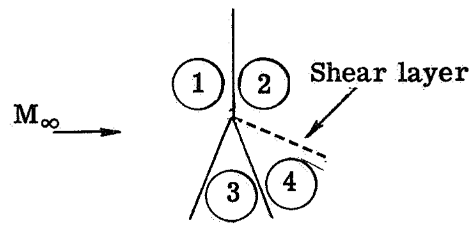
Function VISCJ computes the viscosity by using Sutherland's formula (eq. (A2) of ref. 6). The flow chart and listing are as follows:



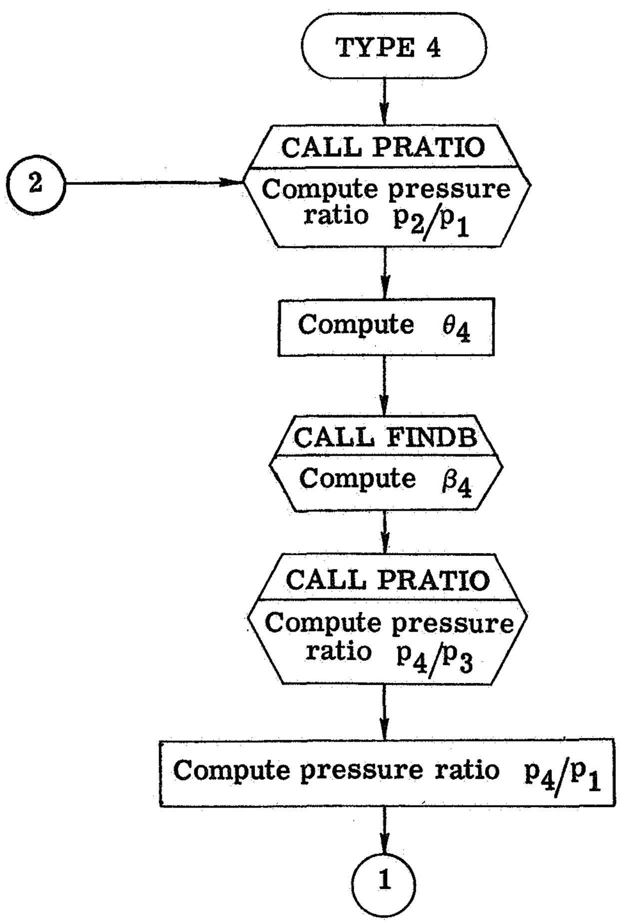
```
      FUNCTION VISCJ (VREF,TREF,T,S)
C     FIND VISCOSITY
      VISCJ=VREF*(T/TREF)**1.5*(TREF+S)/(T+S)
      RETURN
      END
```

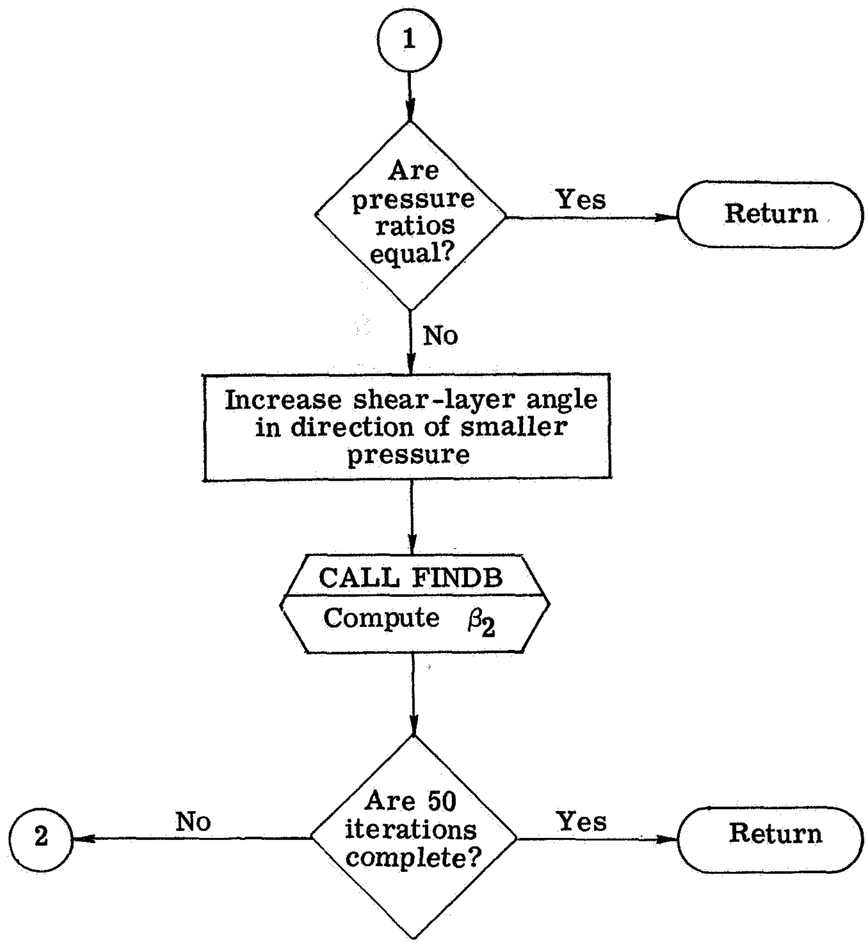
TYP4

Subroutine TYP4 computes the shear-layer deflection angle by iterating until the static pressures in (2) and (4) are equal and the flow directions are parallel on either side of the shear layer for the shock pattern shown in the following sketch:



The flow diagram and listing for this subroutine are as follows:






```
      SUBROUTINE TYP4 (THETAF,BETA2,RM1,RM3,THETAI,THETA4,BETA4,P3OP1,GA
     1MMA,TOL,IERROR)
C     PURPOSE
C     CALCULATE SHEAR LAYER INCLINATION BY MATCHING STATIC PRESSURE AND
C     FLOW DIRECTION ON EITHER SIDE OF SHEAR LAYER. ALSO CALCULATES FLOW
C     ANGLES AND SHOCK ANGLES.
C     DESCRIPTION OF VARIABLES
C       INPUT
C         THETAF = DEFLECTION ANGLE FOR RM1 IN RADIANS. INPUT ESTIMATE
C         BETA2  = SHOCK(STRONG) ANGLE FOR RM1 IN RADIANS. INPUT ESTIMATE
C         RM1    = MACH NUMBER AT INITIAL POINT
C         RM3    = MACH NUMBER AT CONDITION 3.   WEAK SHOCK BETWEEN 3 AND
C         THETAI = DEFLECTION ANGLE FOR RM1 IN RADIANS
C         THETA4 = DEFLECTION ANGLE FOR RM3 IN RADIANS
C         BETA4  = SHOCK(WEAK) ANGLE FOR RM3 IN RADIANS
C         TOL    = CONVERGENCE CRITERIA FOR P4/P1 = P2/P1
C
C        OUTPUT
C         IERROR = 0 NO ERROR
C                  1 ONLY 1 SOLUTION FOUND
C                  2 CONVERGENCE CRITERIAN NOT FOUND
C                  3 NO SOLUTION FOUND
```

```
C
      IT=1
      ISW=0
      METH2=0
      ISOLN=1
      DTHETA=.1
      DTHET=.1
1     SINB2=SIN(BETA2)
      P2OP1=PRATIO(GAMMA,RM1,SINB2)
      THETA4=THETAI-THETAF
C     CALCULATE  WEAK SHOCK SOLUTION
      IERROR=-1
      BETA4=FINDB(GAMMA,RM3,ABS(THETA4),ISOLN,IERROR)
      IF (IERROR-3) 2,14,14
2     P4OP3=PRATIO(GAMMA,RM3,SIN(BETA4))
      P4OP1=P4OP3*P3OP1
      IF (ABS(P2OP1-P4OP1)-TOL) 12,3,3
3     IF (P2OP1-P4OP1) 4,12,7
4     THETAF=THETAF+DTHETA
      IF (ISW) 6,5,10
5     ISW=1
      GO TO 10
6     DTHETA=DTHETA/10.
      THETAF=THETAF-DTHETA
      GO TO 10
7     THETAF=THETAF-DTHETA
      IF (ISW) 10,9,8
8     DTHETA=DTHETA/10.
      THETAF=THETAF+DTHETA
      GO TO 10
9     ISW=-1
C     CALCULATE STRONG SHOCK SOLUTION
10    IERROR=-1
      BETA2=FINDB(GAMMA,RM1,ABS(THETAF),2,IERROR)
      IT=IT+1
      IF (IERROR-3) 11,20,20
11    IF (IT-50) 1,1,12
C                                ITERATION ON P4=P5 IS COMPLETED
12    THFDEG=THETAF*180./3.1416
      RETURN
C        USE 2 STRONG SHOCK SOLUTIONS IF P2.GT.P4
13    IF (P2OP1.LT.P4OP1) RETURN
      IF (METH2.GT.0) RETURN
      METH2=1
      THETAF=0.
      BETA2=1.5708
      ISOLN=2
      DTHETA=-.1
      DTHET=.1
      ISW=0
      IT=1
      WRITE (6,21)
      GO TO 1
14    IF (ISW) 19,15,19
C     BAD INITIAL GUESS
15    THETAF=THETAF+DTHET
16    IF (THETAF-THETAI) 10,17,17
C                THETAF INCREMENTED TOO FAR
17    IF (DTHET-.001) 13,18,18
18    DTHET=DTHET/2.
      DTHETA=SIGN(DTHET,DTHETA)
      THETAF=THETAF-DTHET
      GO TO 16
```

```
C     HAVE INCREMENTED THETAF TOO FAST
19    DTHETA=DTHETA/2.
      THETAF=THETAF-ISW*DTHETA
      IF (ABS(DTHETA)-.001) 13,13,10
C                    NO SOLUTION FOR BETA2
20    IF (ISW) 19,17,19
C
21    FORMAT (/28HTRY 2 STRONG SHOCK SOLUTIONS)
      END
```

PART VIII – PROGRAM APPLICATIONS

This section briefly discusses where the various types of interference patterns may occur and how the programs may be used to compute the peak pressures and peak heat transfer on a practical configuration such as the mated space shuttle (orbiter, rockets, and fuel tank). Shock interference patterns can occur on the nose and between the individual bodies (during the ascent phase of the trajectory), as shown in figure 11. These patterns may also appear on the leading edges of wings and control surfaces, as shown in figure 12. The highest interference heating will exist in regions where subsonic flow is present and either a supersonic jet (type IV) or attaching shear layer (type III) is formed.

The undisturbed flow field over a complex vehicle can be computed with various methods. In fact, complete numerical solutions of the inviscid equations for an arbitrary body at angle of attack are currently under development. Various approximate techniques such as in references 20 and 21 are available now. Once the conditions in the local inviscid flow field, the state of the surface boundary layer, and the approximate location and type of interference pattern are known, the peak pressure and heating can be determined by using the appropriate program. It should be noted, however, that these computer programs must rely on some empirical inputs such as impinging shock angles, shock length, and in the case of the supersonic jet, some relation for the shock standoff distance. Real-gas effects must obviously be considered for high velocities.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., February 12, 1973.

Authors' initials		Division Chief's initials

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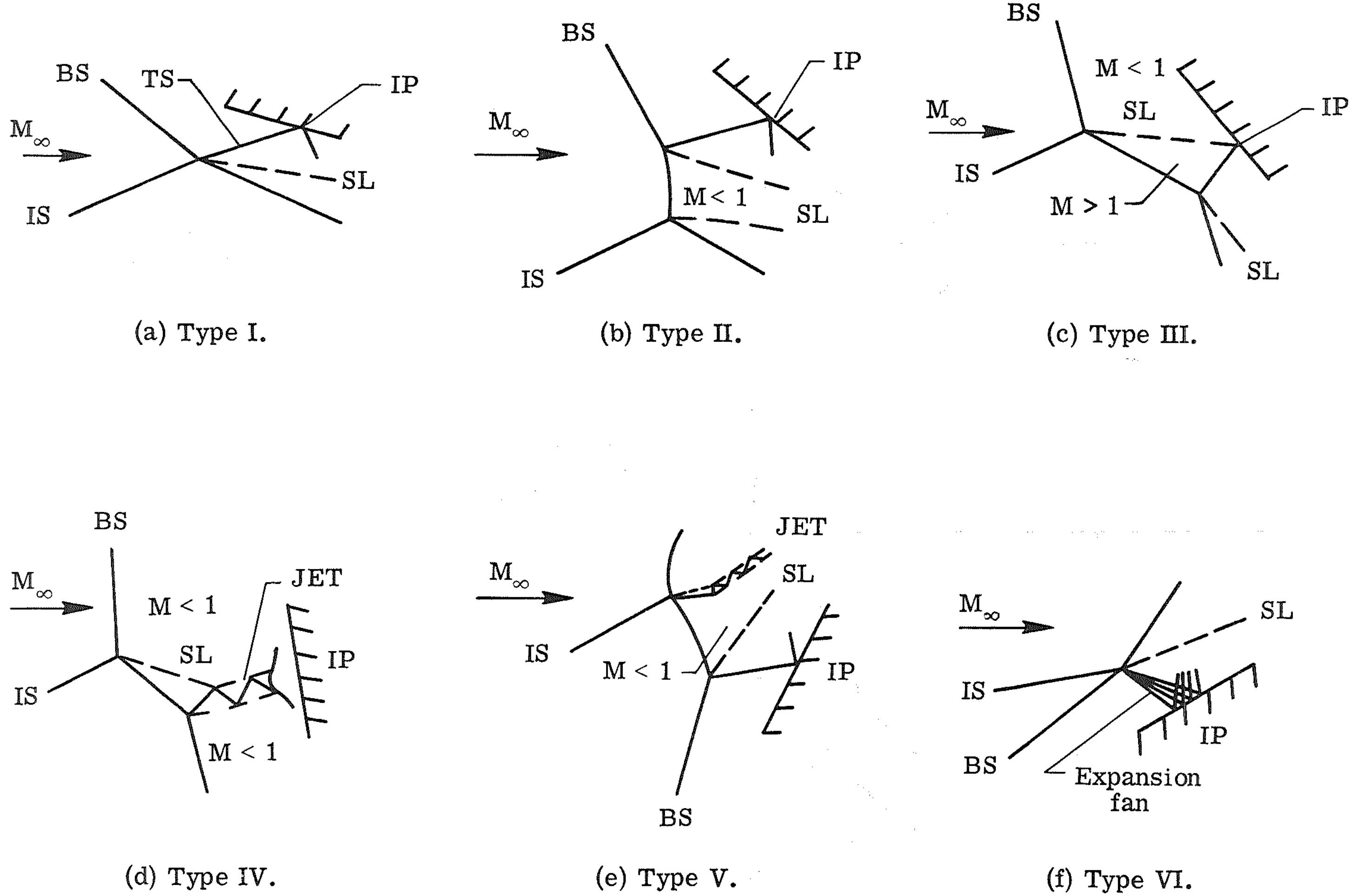

Figure 1.- Six types of shock interference patterns.

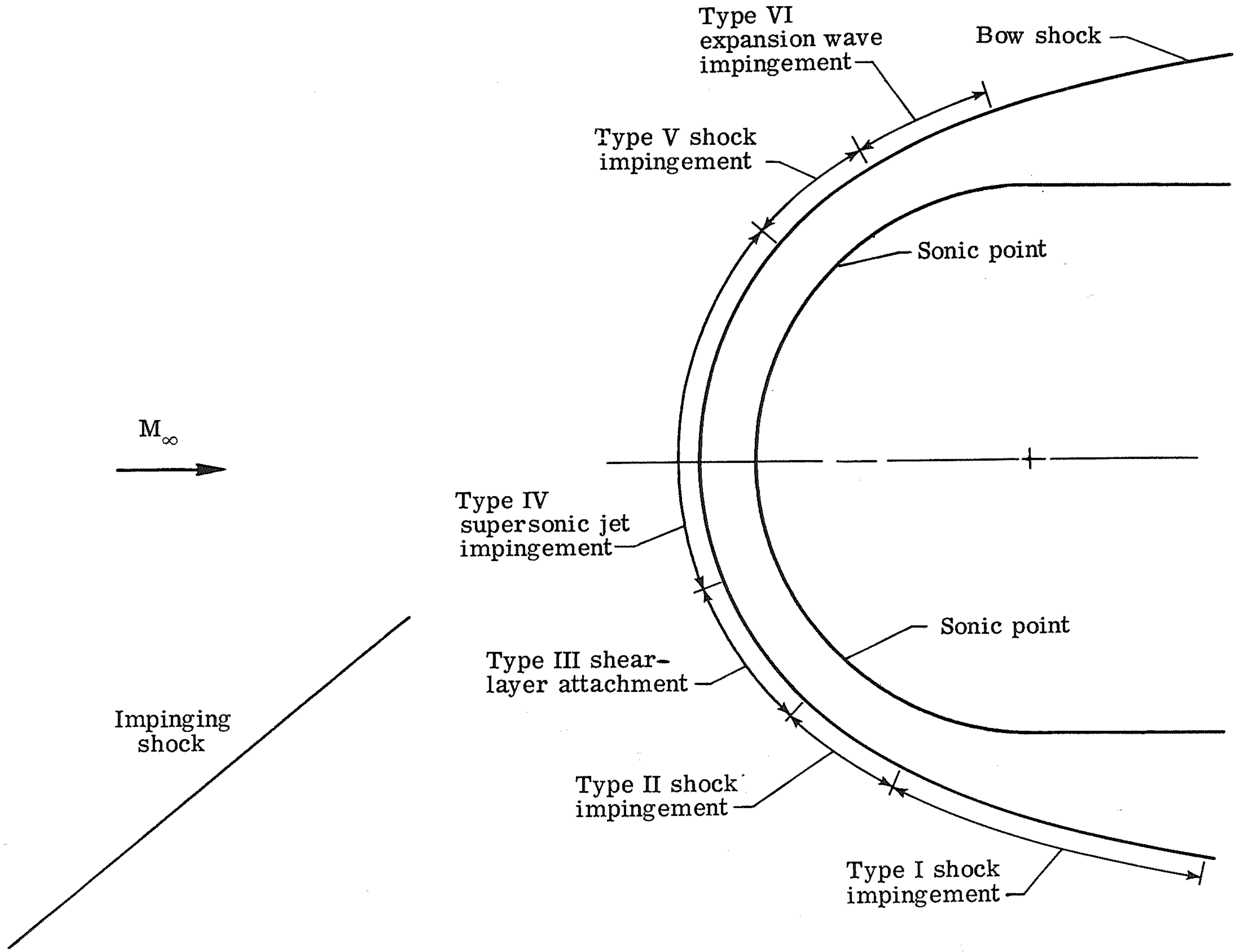

Figure 2.- Location of the types of interference on a hemisphere.

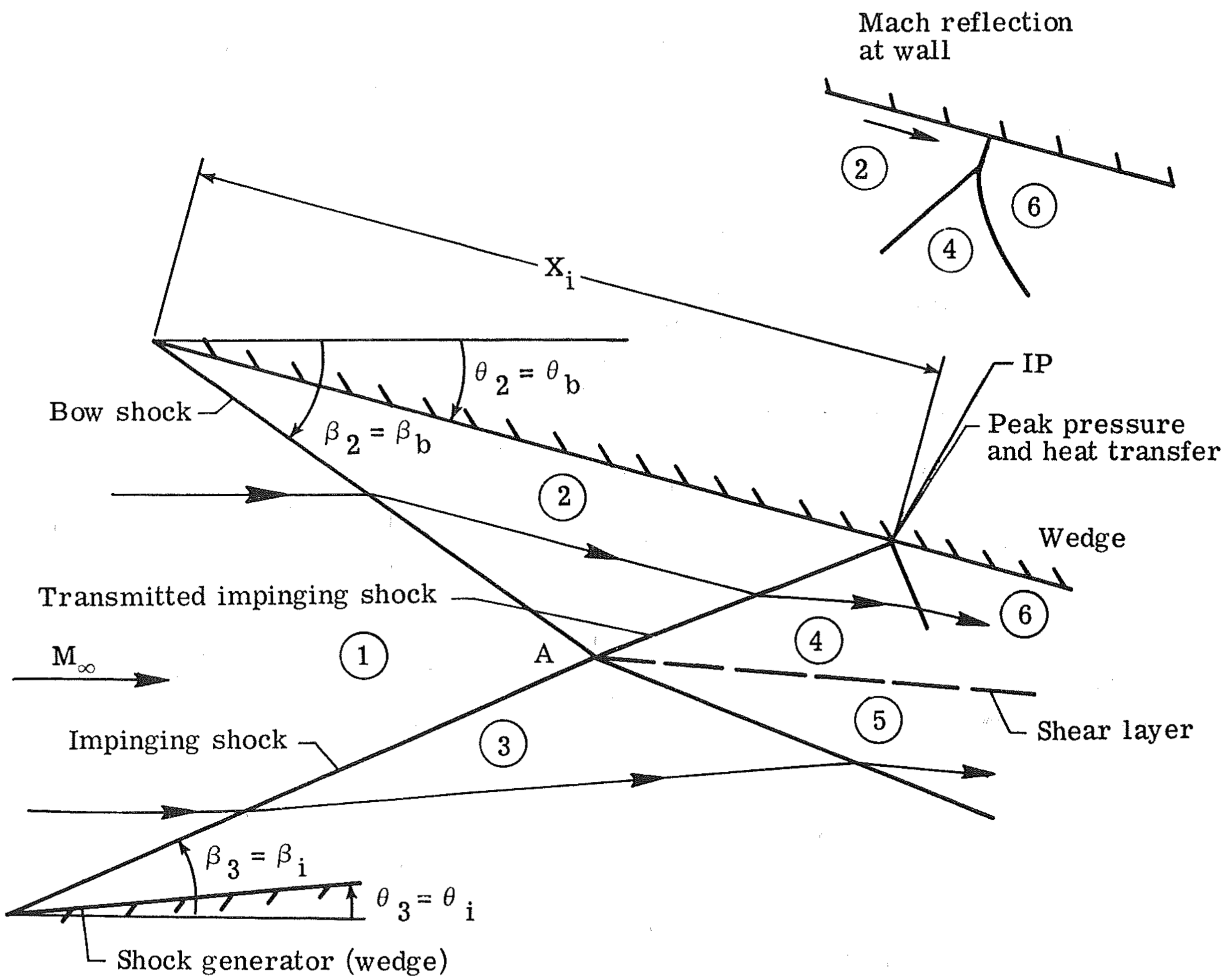

Figure 3.- Type I shock interference pattern.

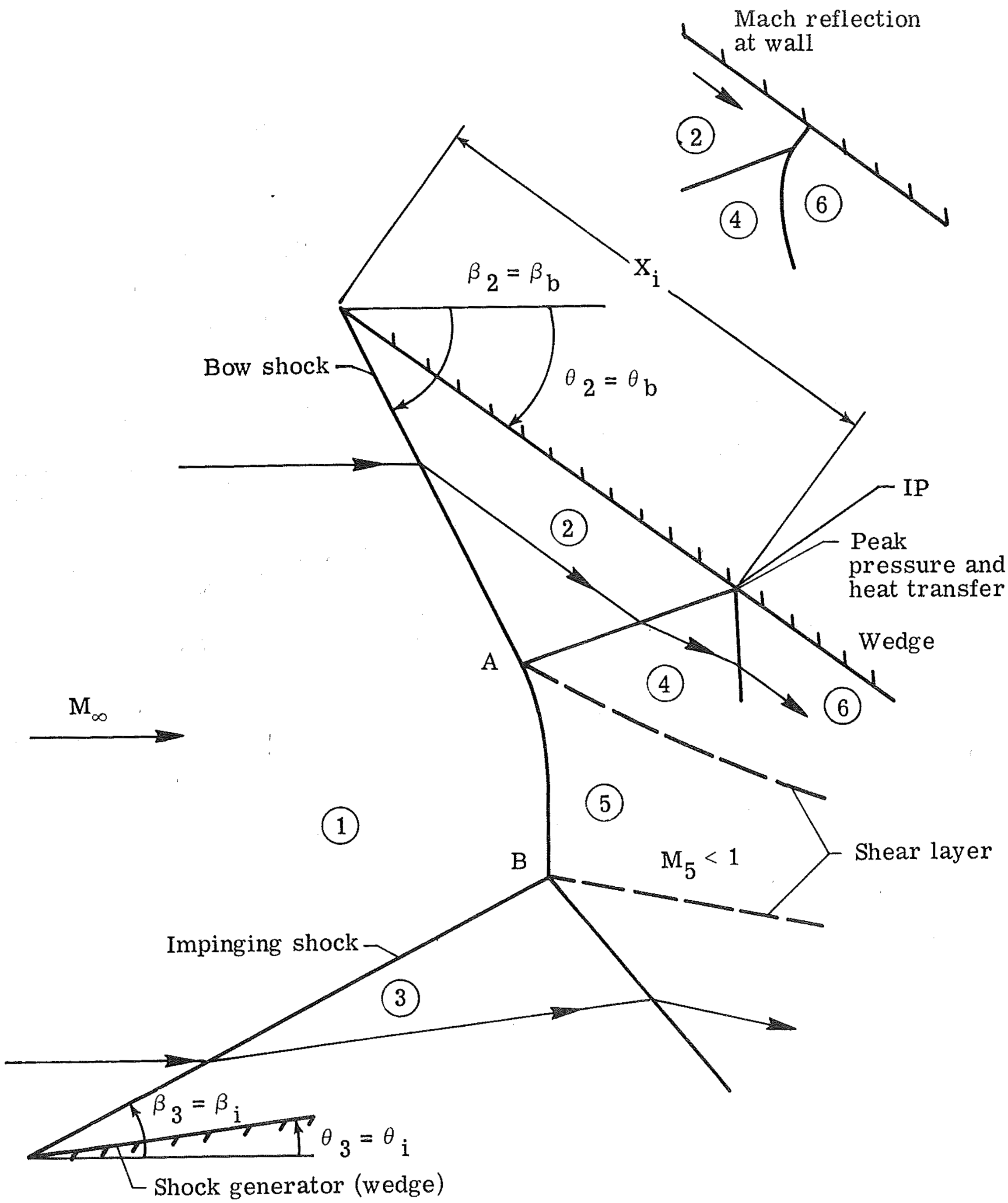

Figure 4.- Type II shock interference pattern.

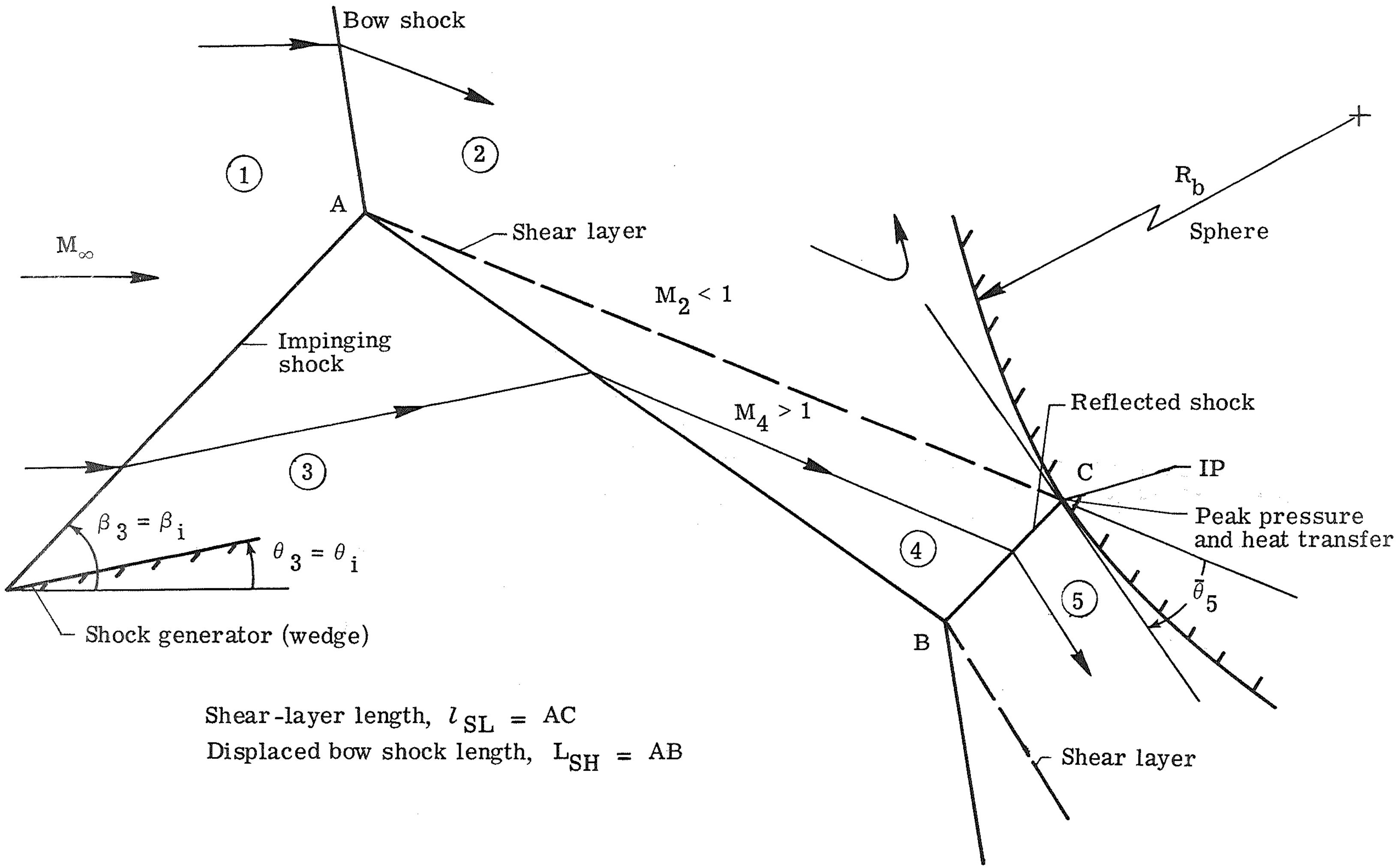

Figure 5.- Type III shock interference pattern.

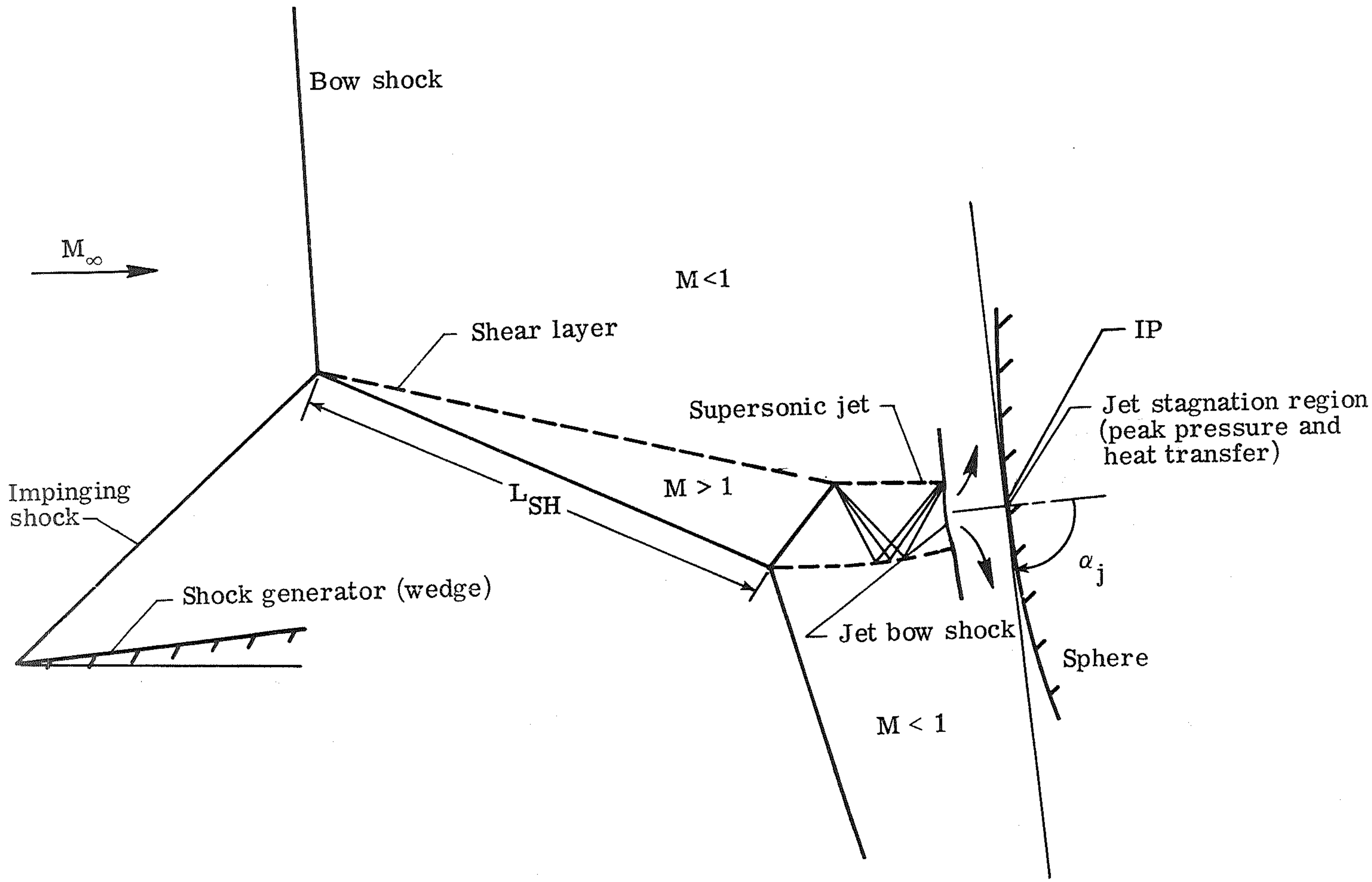

Figure 6.- Type IV shock interference pattern.

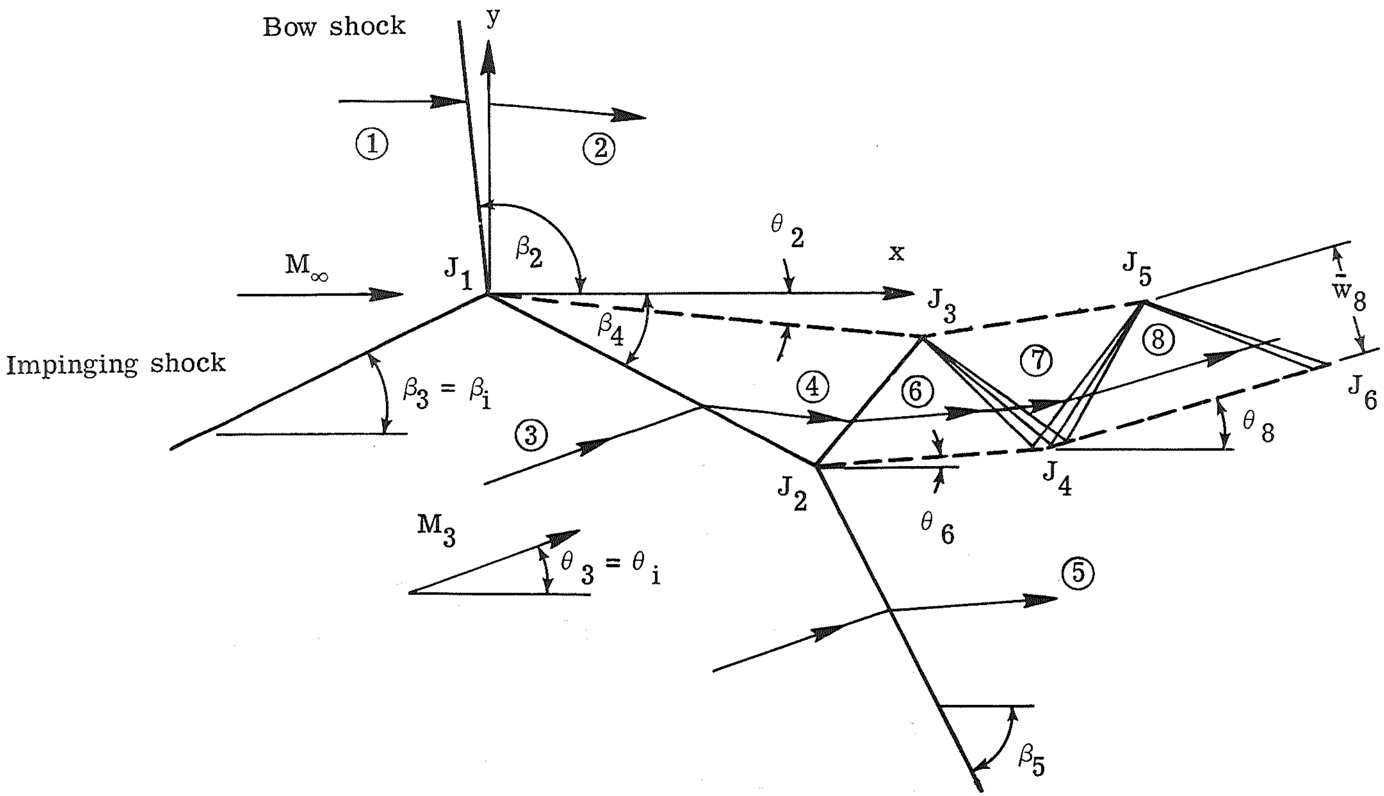

Figure 7.- Type IV shock and jet configuration.

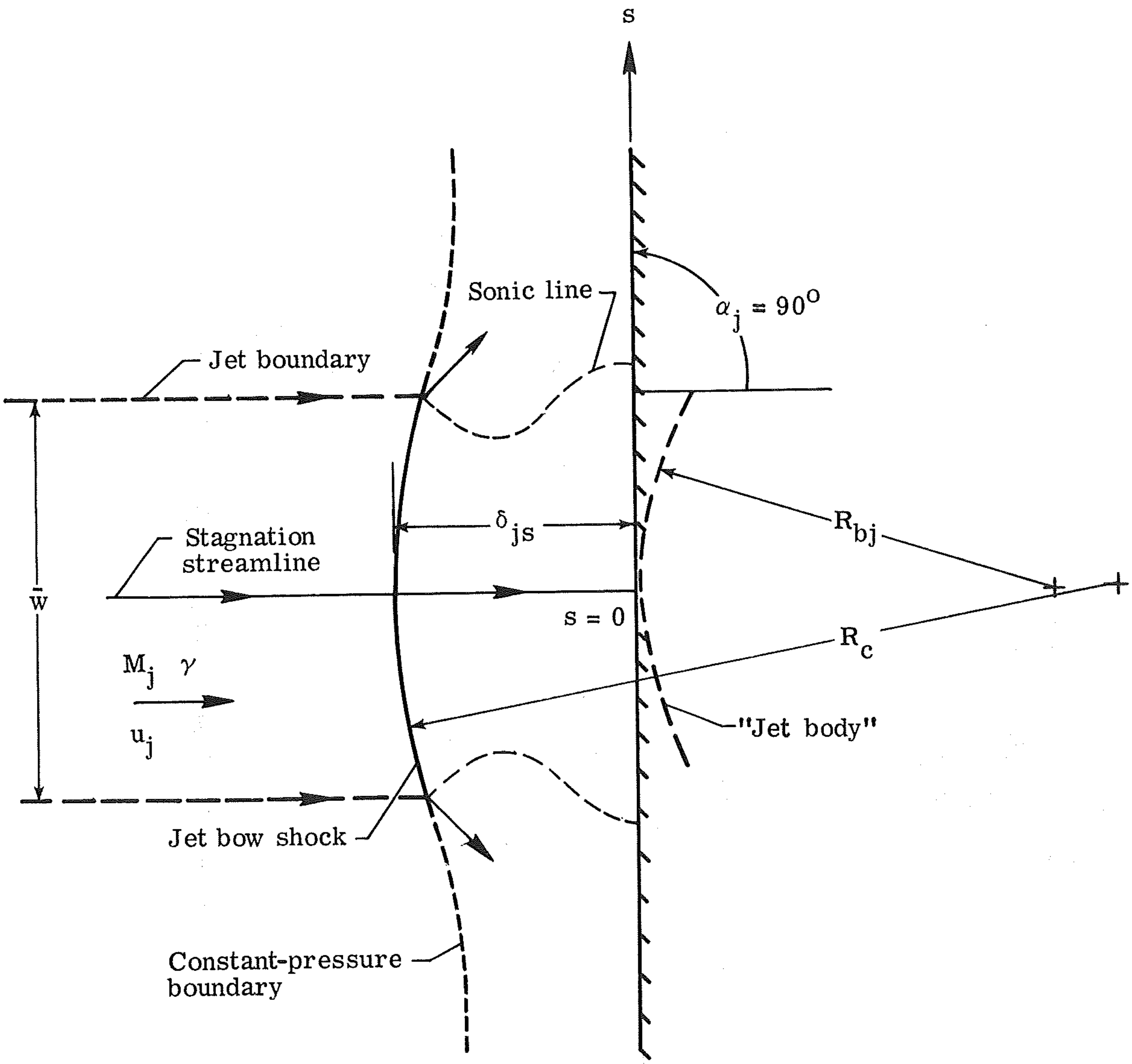

Figure 8.- Normal jet impingement model for $M_j < 2.8$ (ref. 14).

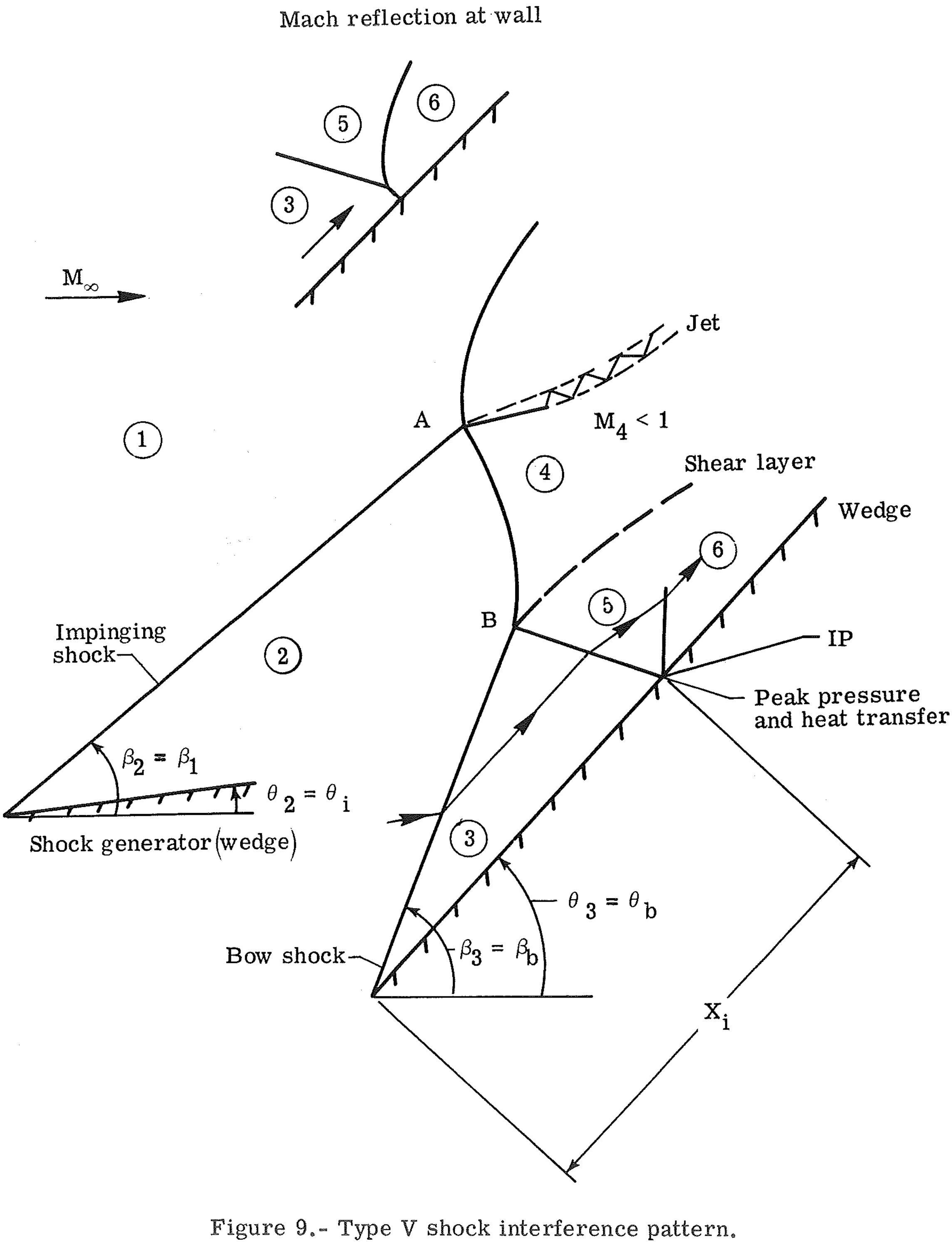

Figure 9.- Type V shock interference pattern.

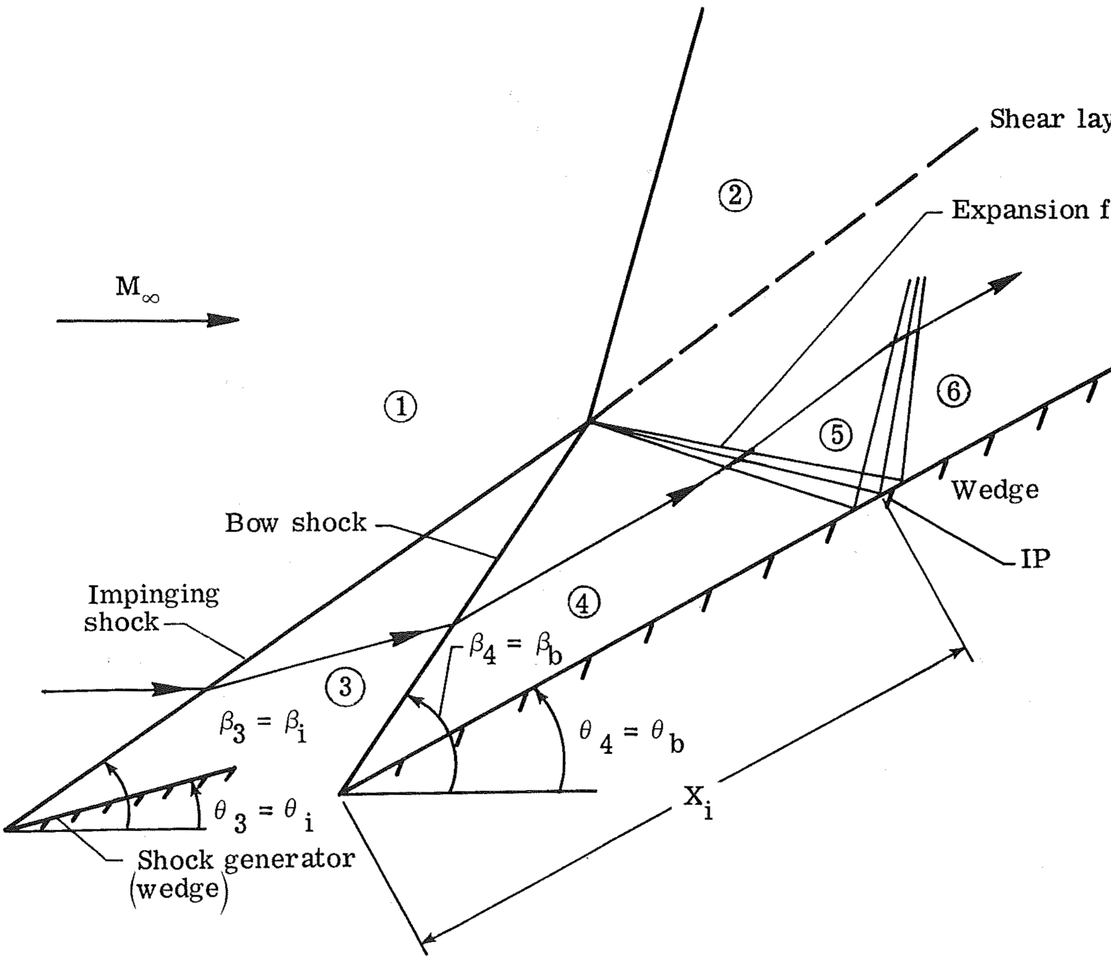

Figure 10.- Type VI shock interference pattern.

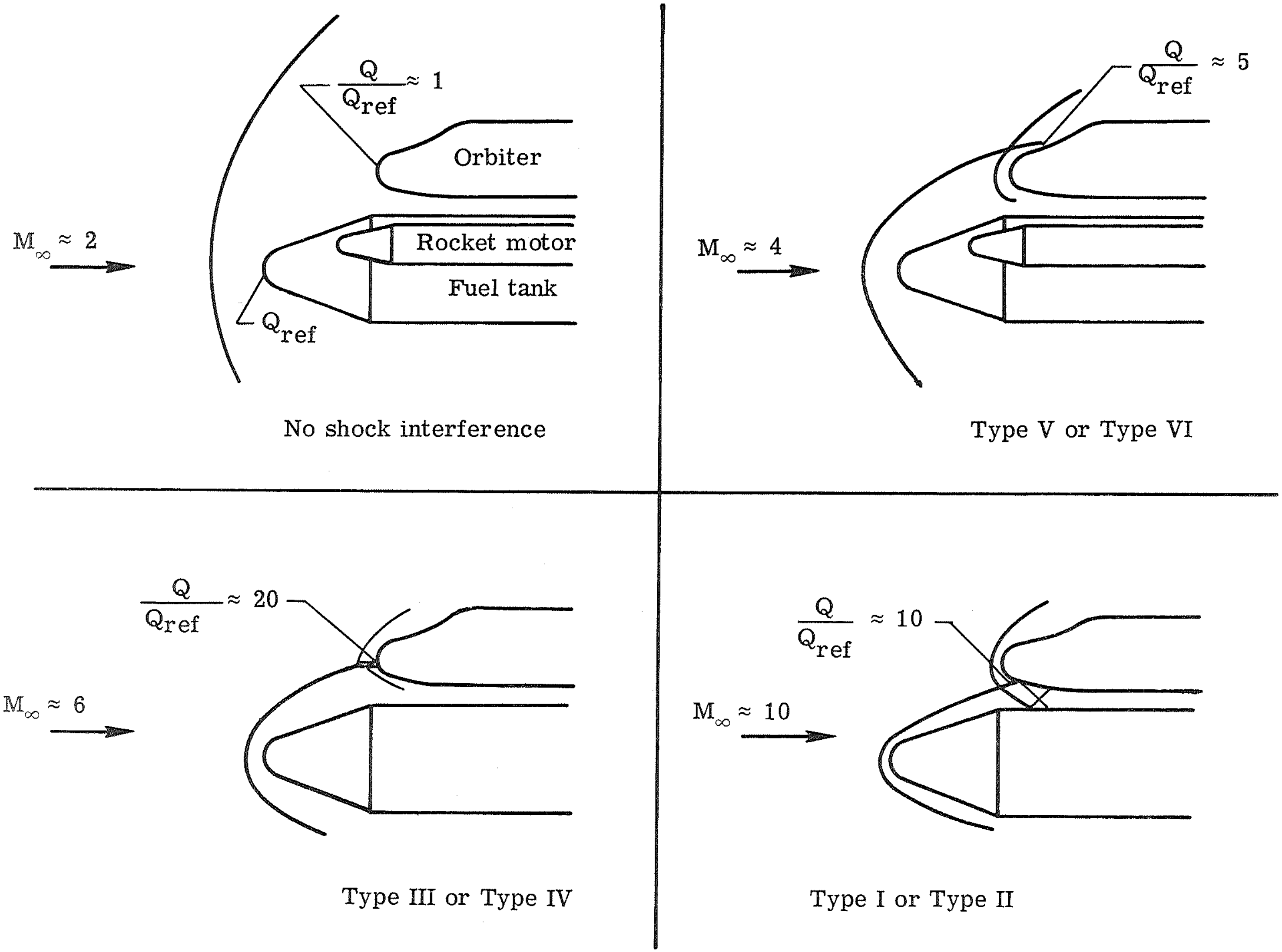

Figure 11.- Shock interference heating during ascent of a mated shuttle configuration.

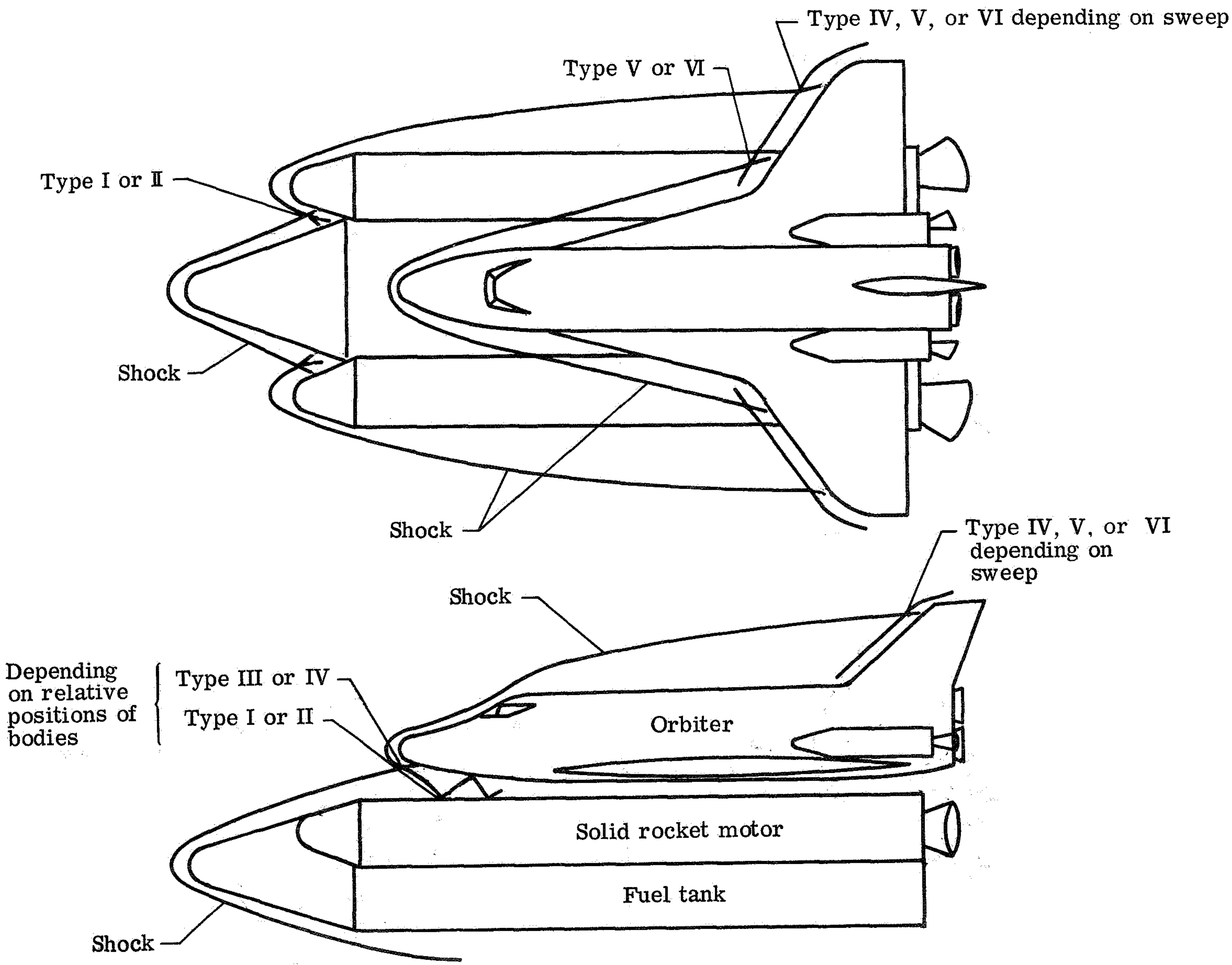

Figure 12.- Locations of types of interference heating on mated configuration at $M_\infty \approx 20$.

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